The future of τ $g-2$

Team 15
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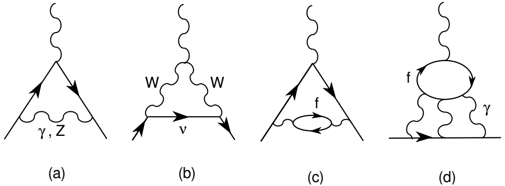
Anomalous magnetic moment of the τ

- Generalized $\tau\tau\gamma$ vertex:

$$\Gamma^{\alpha}_{\tau} = eF_1(q^2)\gamma^{\alpha} + \frac{ie}{2m_\tau}F_2(q^2)\sigma^{\alpha\mu}q_\mu + \frac{e}{2m_\tau}F_3(q^2)\sigma^{\alpha\mu}q_\mu\gamma_5 + \ldots$$

  - $F_1(0) = 1 \rightarrow$ electric charge
  - $F_2(0) = a_\tau \equiv \frac{g_\tau - 2}{2} \rightarrow$ AMM
  - $F_3(0) = -\frac{2m_\tau d_\tau}{e_\tau} \rightarrow$ EDM
- $a^{SM}_\tau = a^{QED}_\tau + a^{EW}_\tau + a^{HLO}_\tau + a^{HHO}_\tau$
- SM predictions:
  - $a^{SM}_\tau = 11772(5) \times 10^{-8}$
  - $d^{SM}_\tau < 10 \times 10^{-34}$ e cm
- SUSY radiative corrections $\delta a_\tau \propto m^2_\tau / \Lambda^2$

$\rightarrow$ $\sim$ 280 times more sensitive to BSM phsyics than a_μ!



arXiv:0705.4264

Accessing the tau AMM experimentally

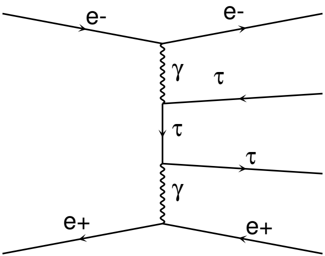
- hard

Accessing the tau AMM experimentally

- τ lifetime $\sim 0.3\,\mathrm{ps} \rightarrow$ spin precession technique not feasible
+ Colliding stuff is more fun anyway

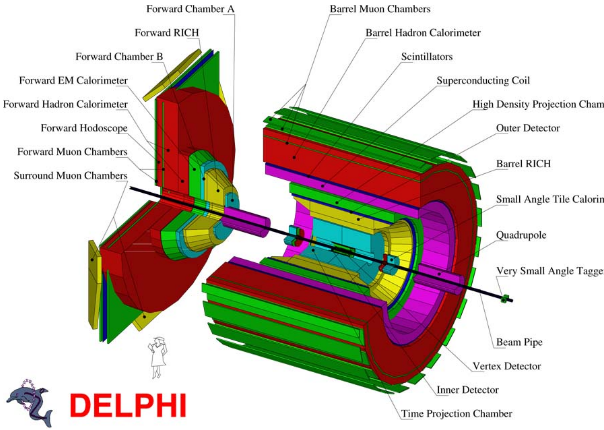
Idea: Use photon fusion in e^+e^- collisions!

- Two vertices sensitive to a_τ
- $\sigma_{e^+e^-\rightarrow e^+e^-\tau^-\tau^+} \propto \log(\frac{s}{m_e^2})^2 \log(\frac{s}{m_\tau^2})$
- Possible to probe low q^2 values



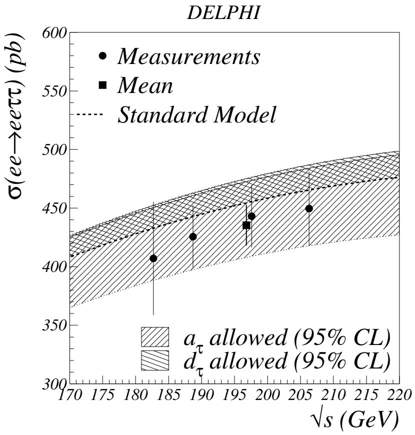
DELPHI measurement: current best limit

- LEP2 experiment running between 1997 and 2000
- $\mathcal{L} = 650\,\text{pb}^{-1}$, $\sqrt{s} \in [183, 206]\,\text{GeV}$
- Cross-section measurement of $e^+e^- \rightarrow e^+e^-\tau^+\tau^-$
  - Looking for events with two-τ final state



DELPHI measurement: current best limit

- Cross-section depends on a_τ and d_τ
- Average $\sigma = 429 \pm 17\,\text{pb}$
- $-0.052 < a_\tau < 0.013$, at 95% CL
  - → one order of magnitude away from prediction precision
- $|d_\tau| < 3.7 \times 10^{-16}\,\text{e cm}$ at 95% CL



Future collider menu

Project	Type	Energy[TeV]	Integrated Lumi [ab^{-1}]
ILC	ee	0.25 - 4.0	2 - 4
CLIC	ee	0.38 - 3.0	1 - 5
CEPC	ee	0.091 - 0.240	16.0 - 5.6
FCC-ee	ee	0.091 - 0.365	150 - 1.5
FCC-he	eh	3.5	10^9
LHeC	ep	60/7000	1
eRHIC	eh	0.029 - 0.140	10^9

D. Schulte - Higgs Factories, Granada 2019

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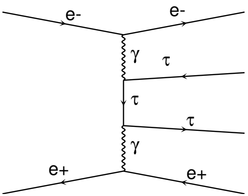
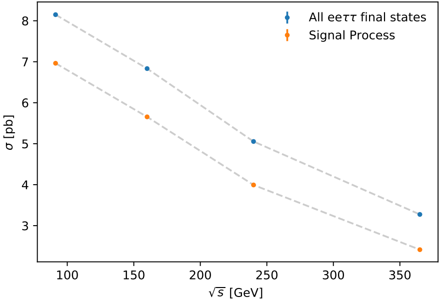
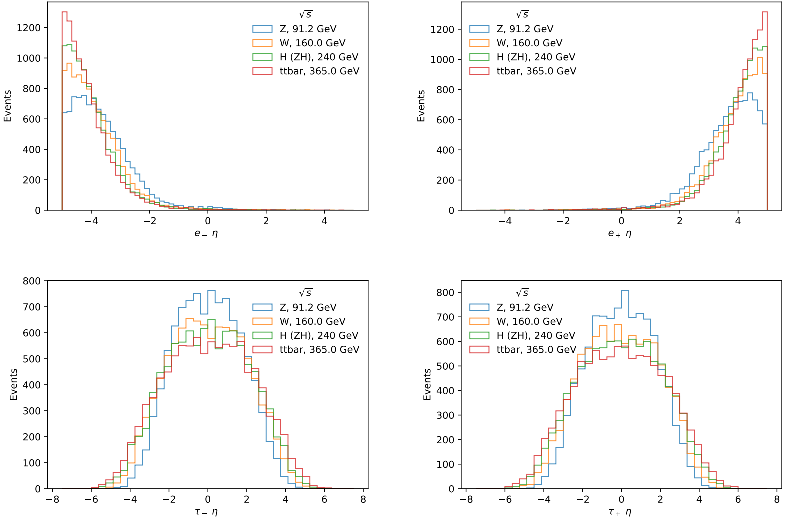
Event Simulation

- Simulated $e^+e^- \to e^+e^-\tau^+\tau^-$ process in FCC-ee style collider with Madgraph at centre of mass energies of 91.2 GeV, 160 GeV, 240 GeV and 365 GeV.
- Dominant contribution is our diagram
- p_T lepton $> 0.5\ \mathrm{GeV}$
- $|\eta| < 5.0$
- 10,000 Events per Run
- Machine parameters from: http://tlep.web.cern.ch/content/machine-parameters

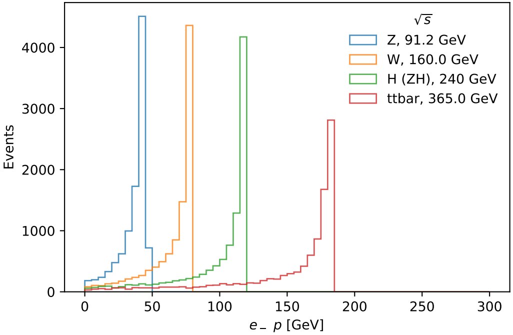


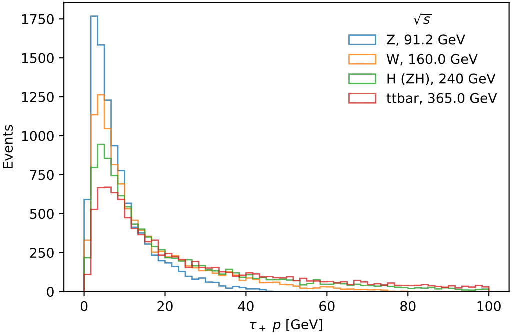


Event kinematics

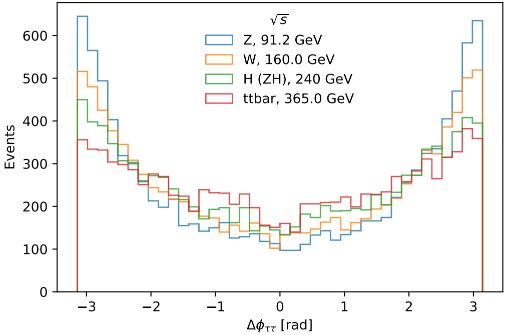


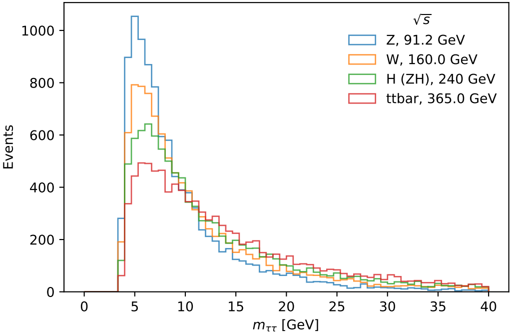
Event kinematics (p)





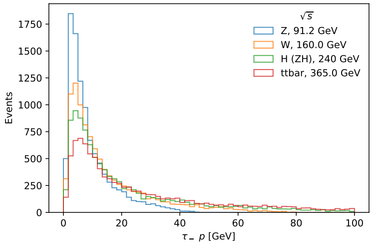
Event kinematics ($\tau\tau$)

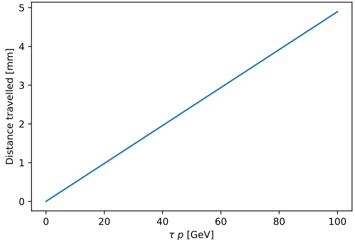




Simulation summary

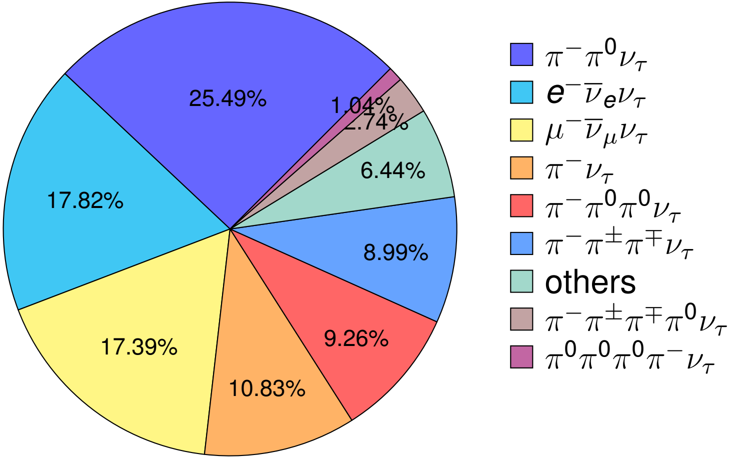
- Taus are produced centrally:
  - Need detector with a central tracker, PID detector, calorimeter, and muon system
- τ p_T range peaks around 10 GeV with long tails
- τ_M =1777 MeV
- $\tau_\tau = 10^{-13}$ s
- Decay length is around 0.5-5 mm
  - High resolution tracker for secondary vertexing





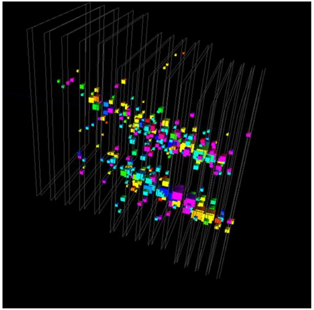
Tau decays

- Many charged particles in final state
  - Cherenkov detector for particle ID
- Hadronic τ decays can include π^0
  - Highly segmented calorimeter for detecting photons from π^0 conversions



Electromagnetic Calorimeter

- Need a very granular calorimeter to reconstructed boosted π^0s from τ decay
- Longitudinally segmented crystals
  - Good distinction between overlapping showers
  - $5 \times 5 \times 5\,\text{mm}^3$ crystal cubes is an ideal size
  - Thickness of 20cm



CALICE test beam

Electron Detection with Forward Electromagnetic Calorimeter

- The scattered electrons will be very energetic
  $\rightarrow$ many interaction lengths needed
  - 20 cm thick ECAL + crystals with interaction length of 1 cm $\rightarrow$ almost all of the scattered energy is contained
  - $\langle E(20\,cm)\rangle = 412.23\ \mathrm{eV}$ assuming an electron with initial energy 200 GeV
- The scattering angle of the electrons and positrons is very small

$\rightarrow$ A VERY forward electromagnetic calorimeter is needed

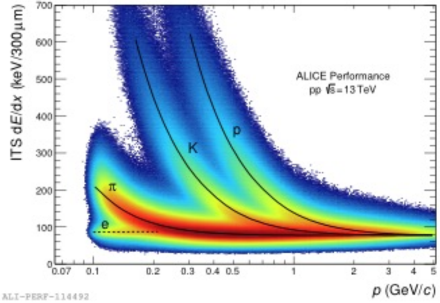
- This calorimeter can be used for coincidence tagging the electron pairs

Background suppresion

- Possible backgrounds:
  - $e^+e^- \to e^+e^-e^+e^-$
  - $e^+e^- \to e^+e^-\mu^+\mu^-$
  - $e^+e^- \to e^+e^-q\overline{q}$

$\Rightarrow$ Good distinction of π, e and μ is crucial for background suppression

- Most commonly used PID detectors struggle to distinguish particles with high momentum
- Cherenkov detector (RICH) filled with C_4F_{10} allows to distinguish particles even at high p



arXiv:1709.00288v1

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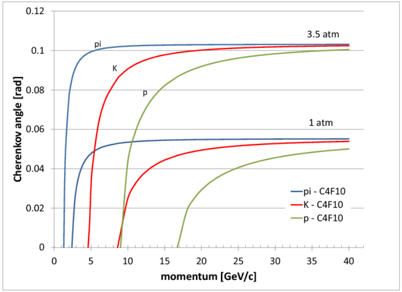
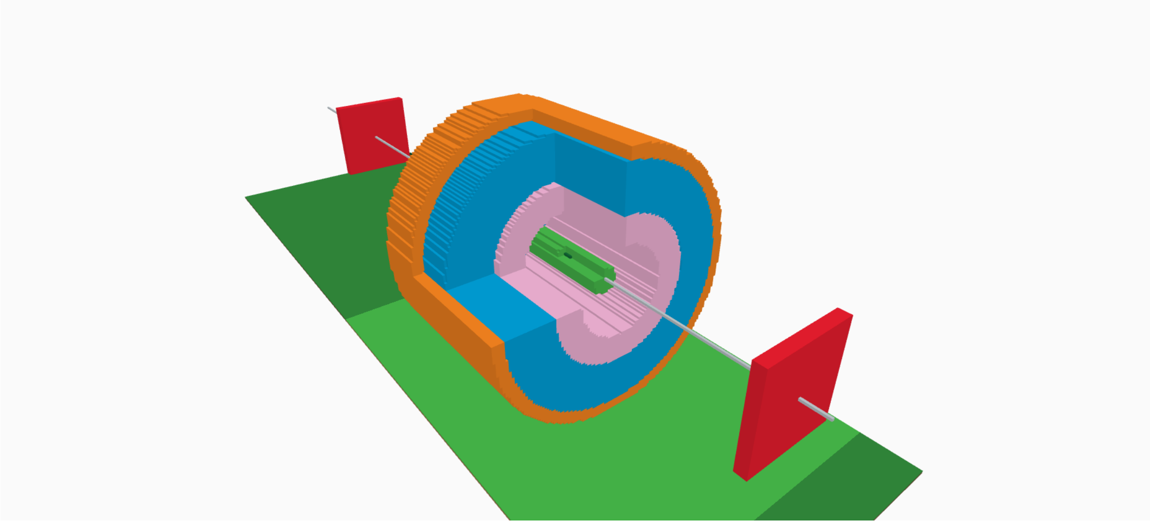


arXiv:1309.5880

Final detector design



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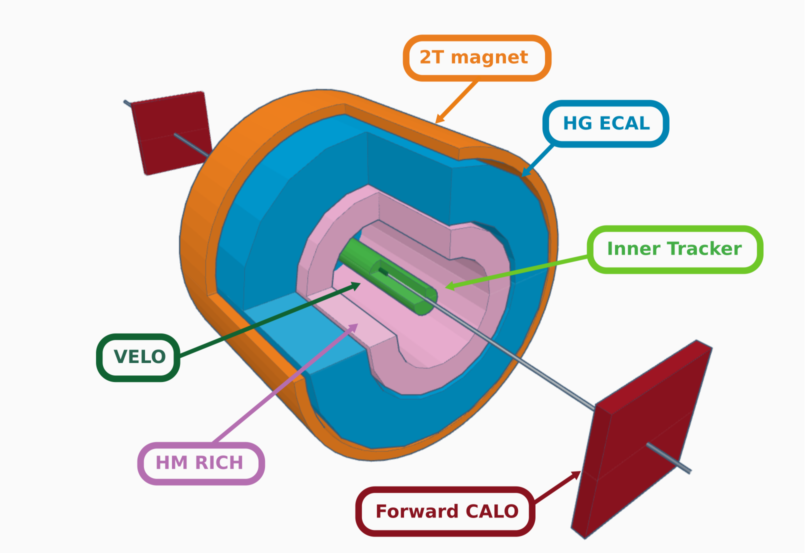


Conclusion & Future Steps

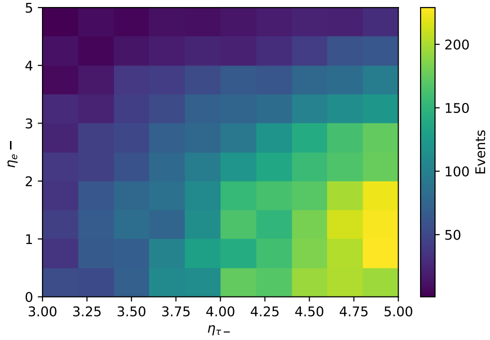
- Better limit than set by DELPHI is possible
  - E.g. CLIC study arXiv:1804.02373v1
  - Two orders of magnitude improvement: $-0.00015 < a_\tau < 0.00017$
- Other possibility is to study heavy ion collisions (arXiv:1908.05180)
- What can be improved:
  - Calculate actual limits
  - More detailed detector design (we would start by adding muon chambers)
- What we learned:
  - Tauons are tricky but very interesting to measure
  - Madgraph is cool
  - Older detectors did impressive measurements

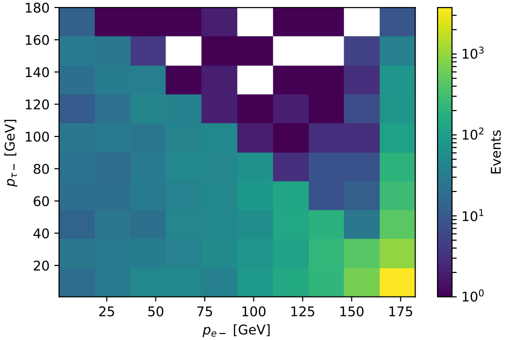
BACKUP

Collaboration	Experimental limit	C. L.
DELPHI	$-0.052 < a_\tau < 0.013$	95%
L3	$-0.052 < a_\tau < 0.058$	95%
OPAL	$-0.068 < a_\tau < 0.065$	95%
Collaboration	Experimental limit	C. L.
BELLE	$-2.2 < Re(d_\tau(10^{-17} ecm)) < 4.5$	95%
	$-2.5 < Im(d_\tau(10^{-17} ecm)) < 0.8$	95%
DELPHI	$-0.22 < d_\tau(10^{-16} ecm) < 0.45$	95%
L3	$\|Re(d_\tau(10^{-16} ecm))\| < 3.1$	95%
OPAL	$\|Re(d_\tau(10^{-16} ecm))\| < 3.7$	95%
ARGUS	$\|Re(d_\tau(10^{-16} ecm))\| < 4.6$	95%
	$\|Im(d_\tau(10^{-16} ecm))\| < 1.8$	95%

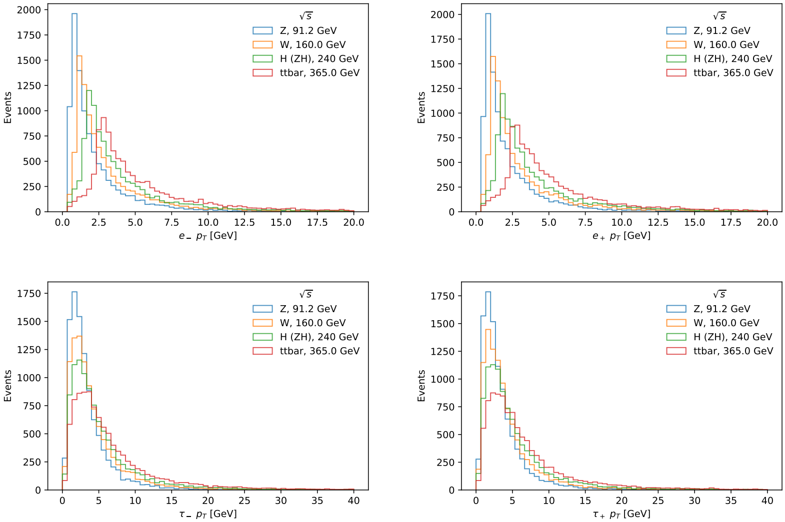
Model	Theoretical limit	C. L.
L3 data	$a_\tau \leq 0.11$	90%
Electroweak Measurements	$-0.004 < a_\tau < 0.006$	95%
LEP1, SLC, LEP2 Data	$-0.007 < a_\tau < 0.005$	95%
Total cross section	$a_\tau < 0.023$	95%
Model	Theoretical limit	C. L.
L3 data	$d_\tau \leq 6 \times 10^{-16} ecm$	90%
Electroweak Measurements	$d_\tau \leq 1.1 \times 10^{-17} ecm$	95%
Cross section	$d_\tau \leq 1.6 \times 10^{-16} ecm$	90%

Event kinematics Correlations

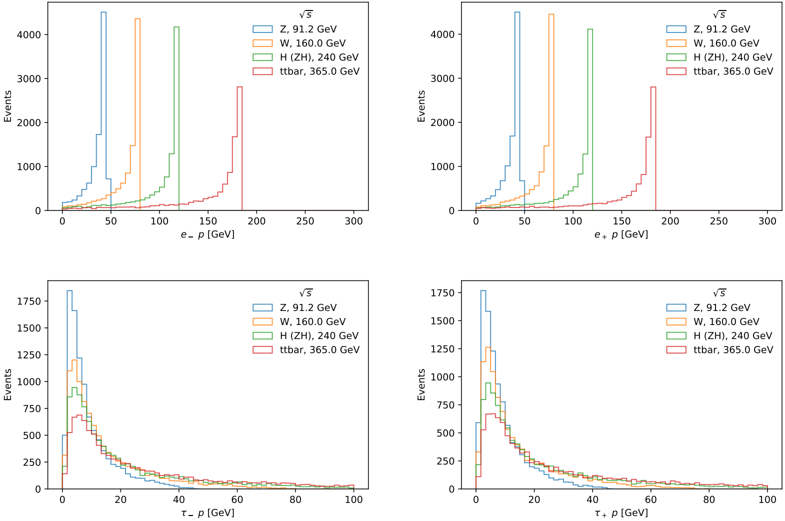




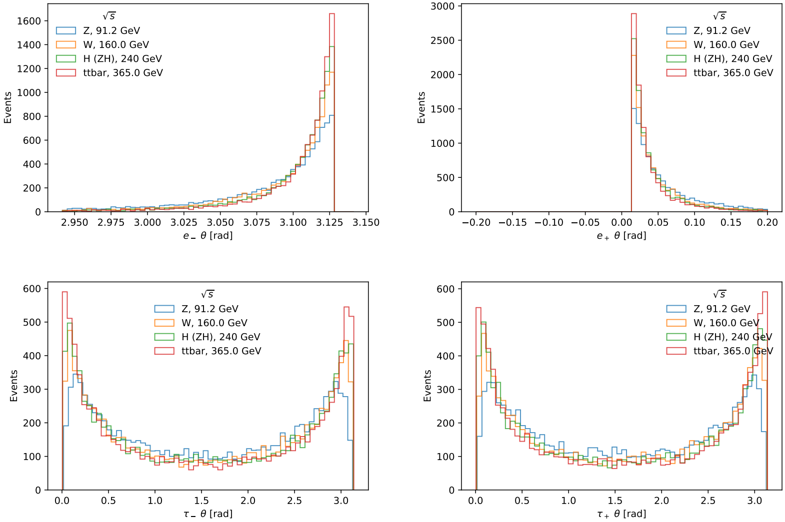
Event kinematics (pT)



Event kinematics (p)



Event kinematics (θ)



Eta