Results on tau physics from HERA

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On behalf of
the H1 and ZEUS collaborations

10th Int. Workshop on Tau Lepton Physics (TAU08)
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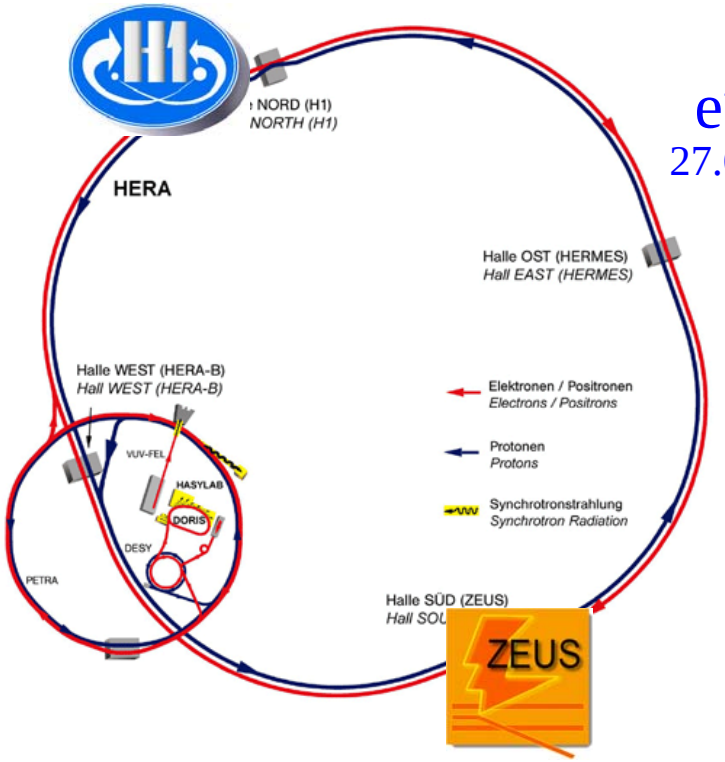
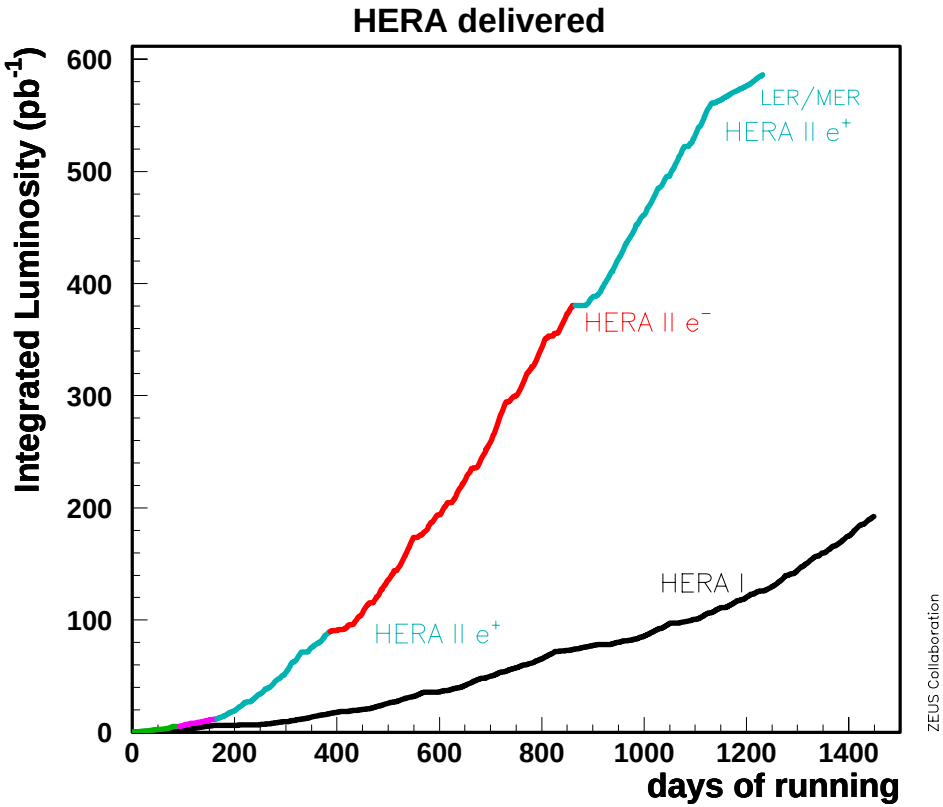
HERA: World's Only *ep* Collider



$\sqrt{s} \sim 318\,\text{GeV}$

e^+/e^- 27.6 GeV → ← p 920 GeV

HERA laid to rest on 30 June 2007.



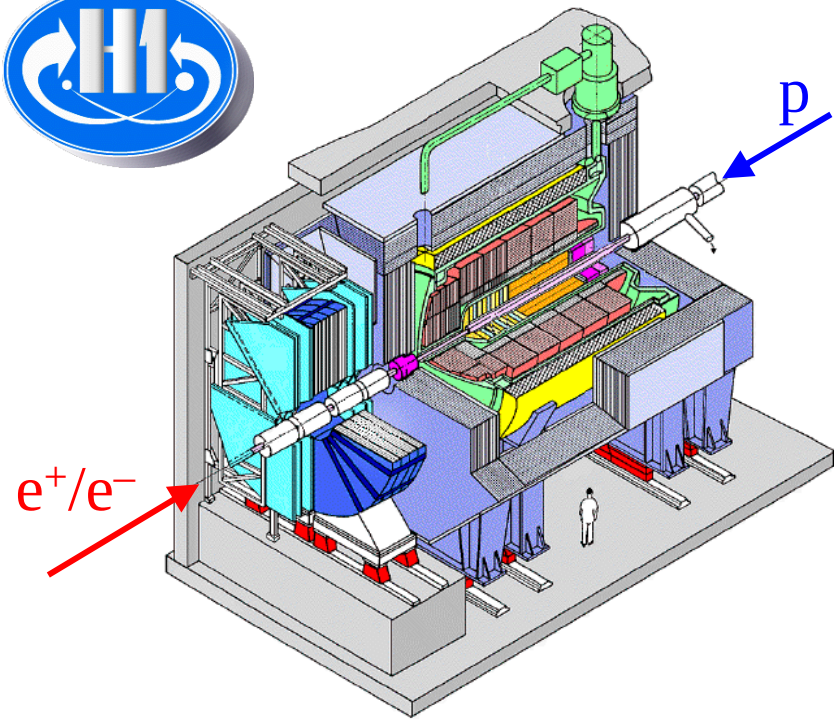
HERA–I (1992~2000) : L~120 pb^{-1}/exp.

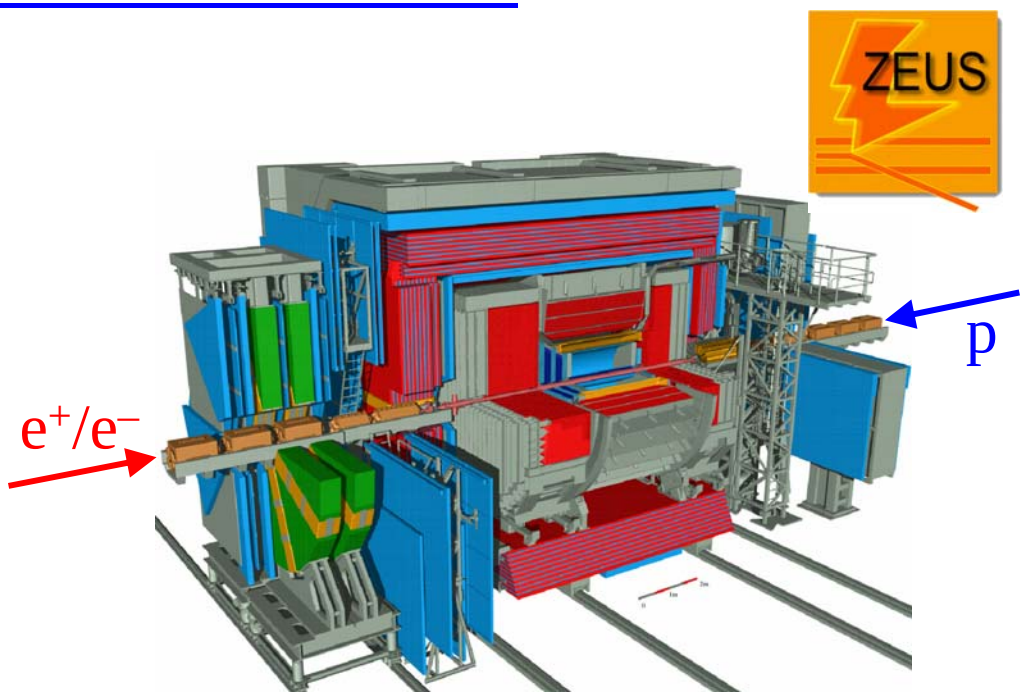
HERA–II (2002~2007) : L~350 pb^{-1}/exp.

- luminosity upgraded
- longitudinally polarized lepton beam
- detector upgrades

→ 0.5 fb^{-1} data for each experiment!

H1 and ZEUS detector





Liquid Argon Calorimeter

fine granularity, excellent tracking

$\sigma(E)/E = 12\%/\sqrt{E}$ for electrons

$\sigma(E)/E = 50\%/\sqrt{E}$ for hadrons

Uranium–scintillator Calorimeter

good hadronic energy resolution

$\sigma(E)/E = 18\%/\sqrt{E}$ for electrons

$\sigma(E)/E = 35\%/\sqrt{E}$ for hadrons

Tau Production at HERA

Tau lepton production is a rare process at HERA!

- $\tau^+\tau^-$ pair–production events
- Isolated τ lepton with missing transverse momentum(P_T^{miss}) events
- Double charged Higgs Search
- Lepton Flavour Violation

$\longrightarrow$ *Tau lepton is important in exotic search.*

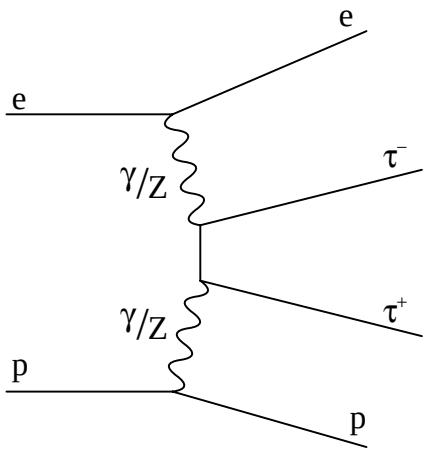
Tau Production at HERA

- $\tau^+\tau^-$ pair–production events
  - Leptonic channel ($\tau^+\tau^- \rightarrow e^{\pm}\mu^{\mp}$)
  - Semi–leptonic channel ($\tau^+\tau^- \rightarrow e^{\pm}had^{\mp}, \mu^{\pm}had^{\mp}$)
  - Hadronic channel ($\tau^+\tau^- \rightarrow had^{\pm}had^{\mp}$)
- Isolated τ lepton with missing transverse momentum(P_T^{miss}) events
- Double charged Higgs Search
- Lepton Flavour Violation

$\tau^+\tau^-$ pair–production (only leptonic) @ ZEUS

$ep \to \tau^+\tau^-(ep)$ HERA–II e^-p data **L=135 pb^{-1}**

ZEUS ZEUS–prel–06–017

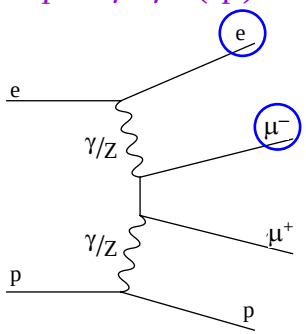


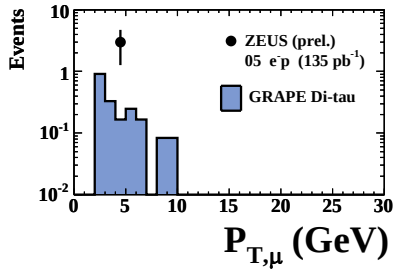
searched for $\tau^+\tau^- \to e^\pm\mu^\mp$

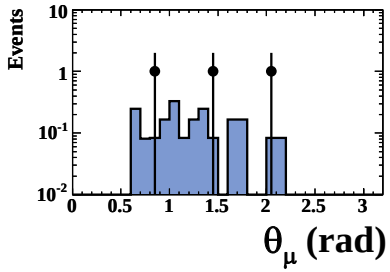
(leptonic decay)

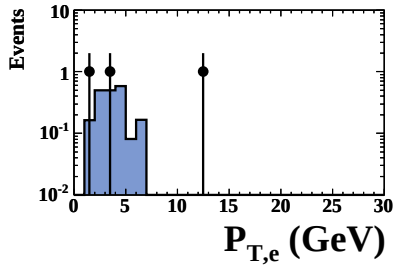
dominant background

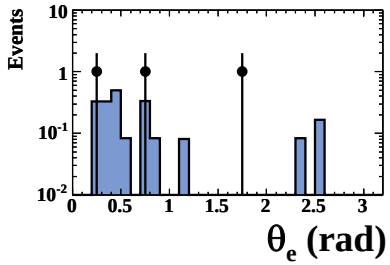
$ep \to \mu^+\mu^-(ep)$

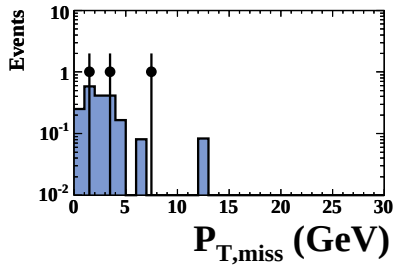


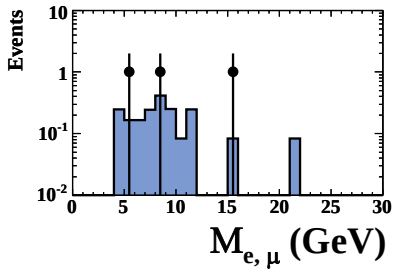












selection criteria

electron	muon
$E_e > 4$ GeV $\theta_e < 2.6$ rad	$p_T^\mu > 2$ GeV 0.6 rad $\lesssim \theta_\mu \lesssim$ 2.8 rad (Acceptance of central tracking detector)
elastic requirements – Number of tracks in event : 1~3 – No energy deposit in ”forward” calorimeter region	

ZEUS e^-p 135 pb^{-1} (prel.)

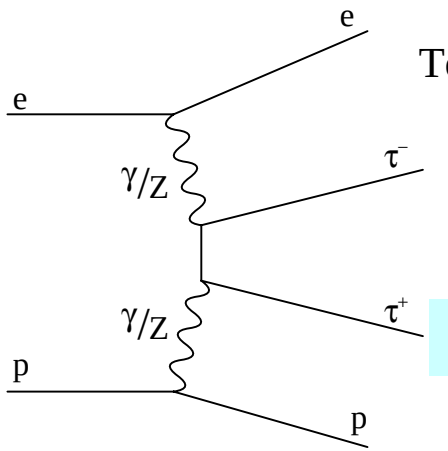
Data	$\tau^+\tau^-$	$\mu^+\mu^-$
3	**2.0 ± 0.8**	**< 0.2**

$\longrightarrow$ Data agree with SM expectation.

$\tau^+\tau^-$ pair–production (incl. hadronic) @ ZEUS

$ep \to \tau^+\tau^-(ep)$ HERA–II $e^{\pm}p$ data **L=364 pb^{-1}**

ZEUS–prel–08–009



$\sigma \sim 10$ pb ($P_T^{\tau} > 5$ GeV)

To study hadronically–decayed τ identification, searched for:

$$\tau^+\tau^- \longrightarrow \begin{cases} e^{\pm} + h^{\mp} + \nu_\tau + \cdots & \text{(BR : ~23%)} \\ h^{\pm} + h^{\mp} + \nu_\tau + \cdots & \text{(BR : ~42%)} \end{cases}$$

more statistics than eμ channel (~6%)

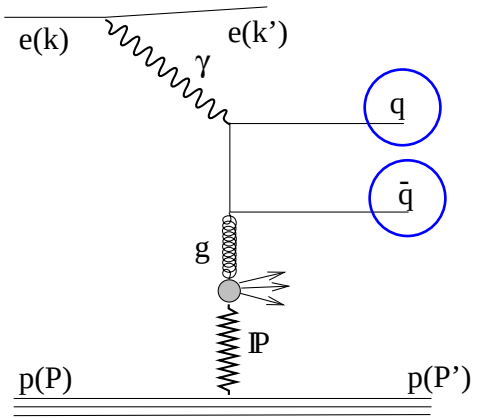
Hadrons from τ decay is identified by ”jet”.

The most difficult thing : separate a τ–jet from quark/gluon induced jets

There are many kinds of large background…

e.g.) diffractive–photoproduction

σ~300 nb (2 jets w/ E_T>4 GeV)



electron	jet
$p_T^e > 5$ GeV & $-2 < \eta_e < 2$ matched track ($p_T^{track} > 3$ GeV)	$p_T^{jet} > 5$ GeV & $-2 < \eta^{jet} < 2$ at least one associated tracks, electron rejection cut
elastic requirements : No energy deposit in forward calorimeter region, Low track multiplicity	

τ–jet ID for $\tau^+\tau^-$ pair–production @ ZEUS

had τ–ID

τ–ID using PDE Range Searching (discriminant)

suggested by T.Carli, B.Koblitz. NIM**A**501(2003)576

- Generalization of one–dimensional PDE approach to *n* dimensions
  - Counts number of signal and background events (training sample) in *"vicinity"* *V* of the test event
  - Implemented in *T*MVA

Discrimination value

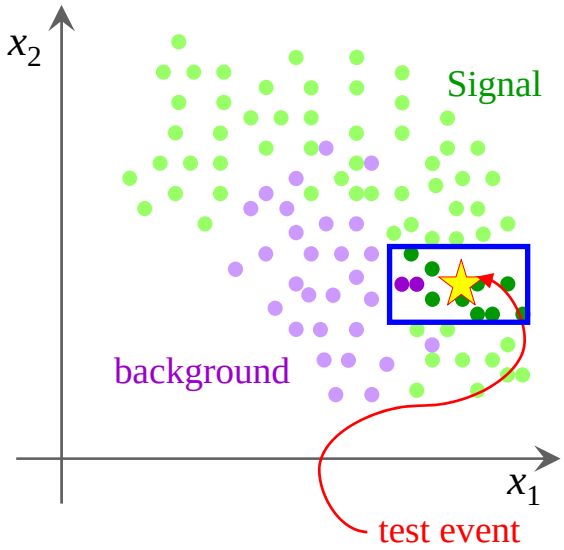
#signal events in *V*

#all signal events

$$D(i_{event},V) = \frac{n_S(i_{event},V) / N_S}{n_S(i_{event},V) / N_S + n_B(i_{event},V) / N_B}$$

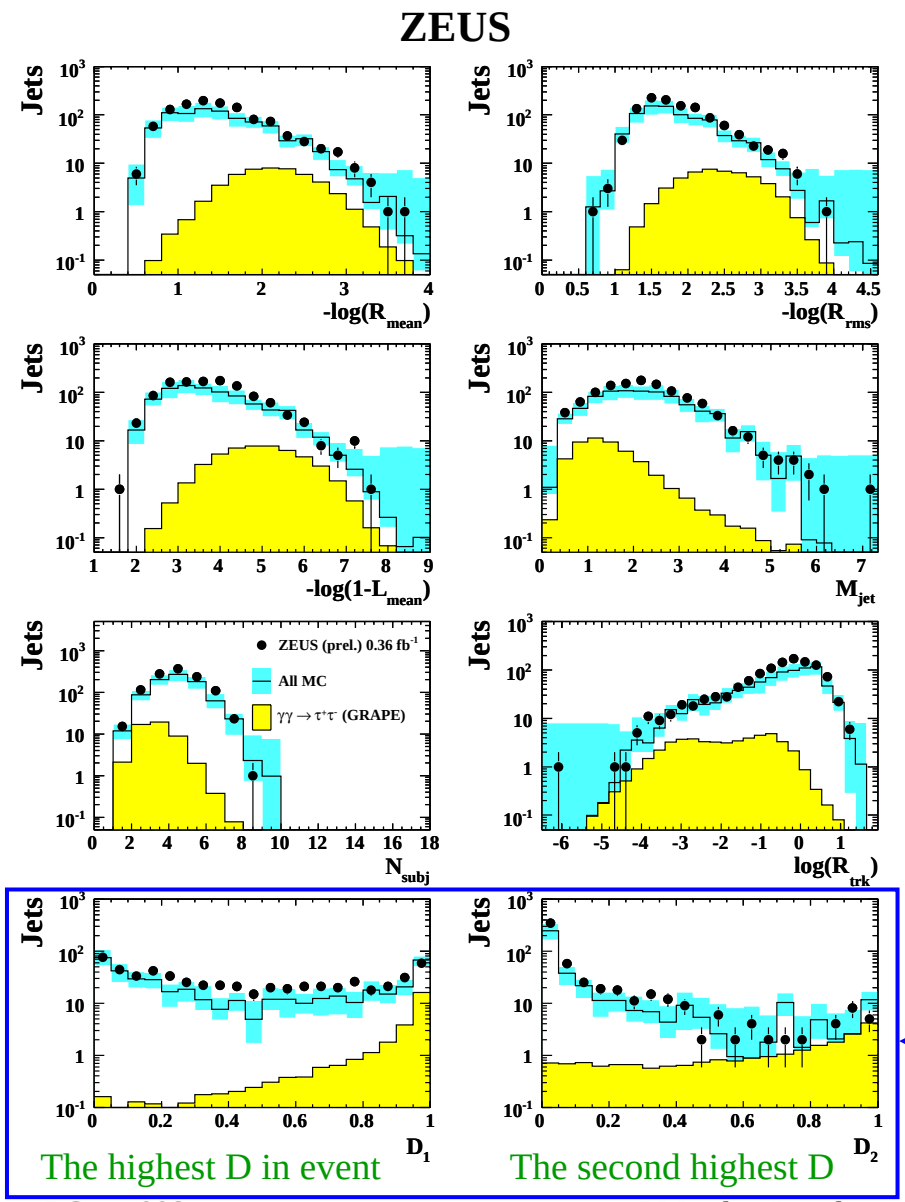
#background events in *V*

#all background events



- 6 variables are inputted to discriminant, then evaluate discrimination value. (next slide)

τ–jet ID for $\tau^+\tau^-$ pair–production @ ZEUS



had τ–ID

6 variables are prepared for discriminant.

Rmean, Rrms : 1st and 2nd moment of radial extension

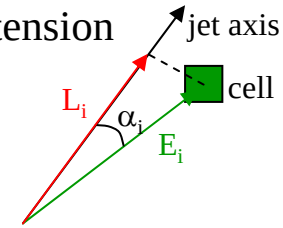
$$Rmean = \langle R \rangle = \frac{\sum_i \{E_i \cdot R_i\}}{\sum_i E_i} \qquad Rrms = \sqrt{\frac{\sum_i E_i \cdot (\langle R \rangle - R_i)^2}{\sum_i E_i}}$$

Mass : invariant mass of clustered CAL cells

$$Mass = \sqrt{(\sum_i E_i)^2 - (\sum_i p_{i,x})^2 - (\sum_i p_{i,y})^2 - (\sum_i p_{i,z})^2}$$

Lmean : 1st moment of longitudinal extension

$$Lmean = \langle L \rangle = \frac{\sum_i E_i \cdot \cos\alpha_i}{\sum_i E_i}$$



Rtrk : The sum of distance between the jet axis and the tracks associated with the jet

$$Rtrk = \sum_i^{Ntrk} \sqrt{(\Delta\eta_i^2 + \Delta\phi_i^2)}$$

Nsubj : Number of subjets ($y_{cut}=5\times10^{-4}$)

← Outputted discrimination value

ZEUS–prel–08–009

Results of $\tau^+\tau^-$ pair–production @ ZEUS

$ep \to \tau^+\tau^-(ep)$ HERA–II $e^{\pm}p$ data **L=364 pb^{-1}**

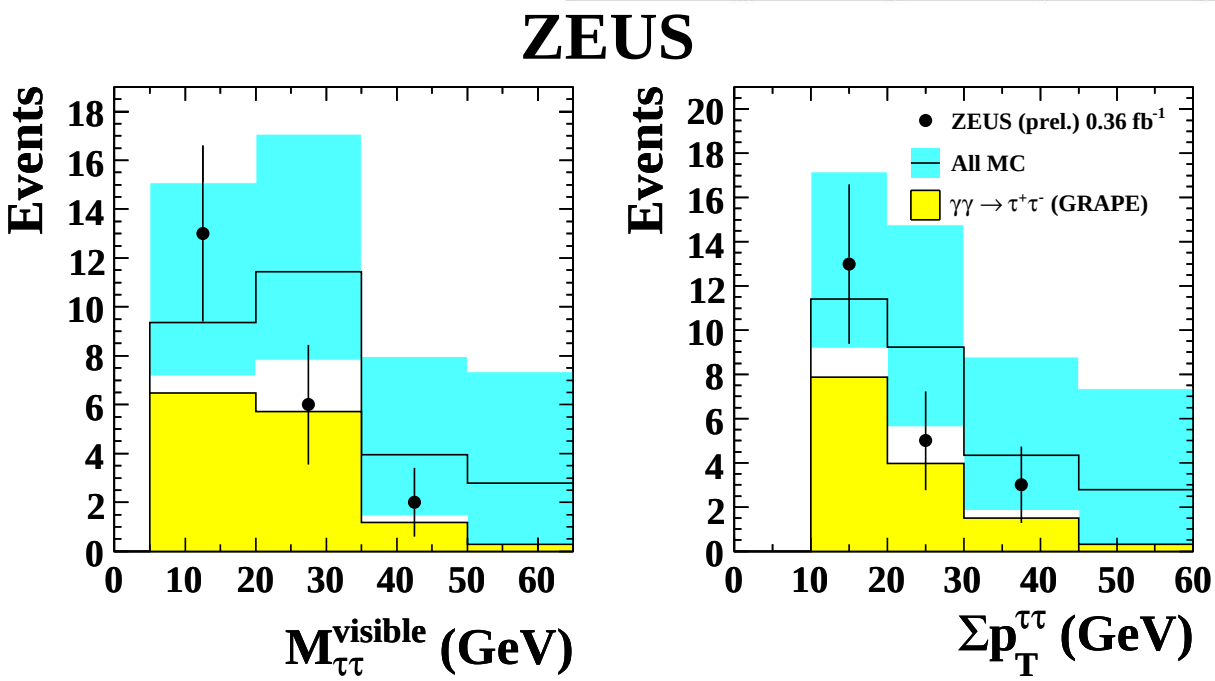
ZEUS–prel–08–009

Discriminant threshold is given for each topology.

Large uncertainty due to
- MC statistics
- PHP scale normalization

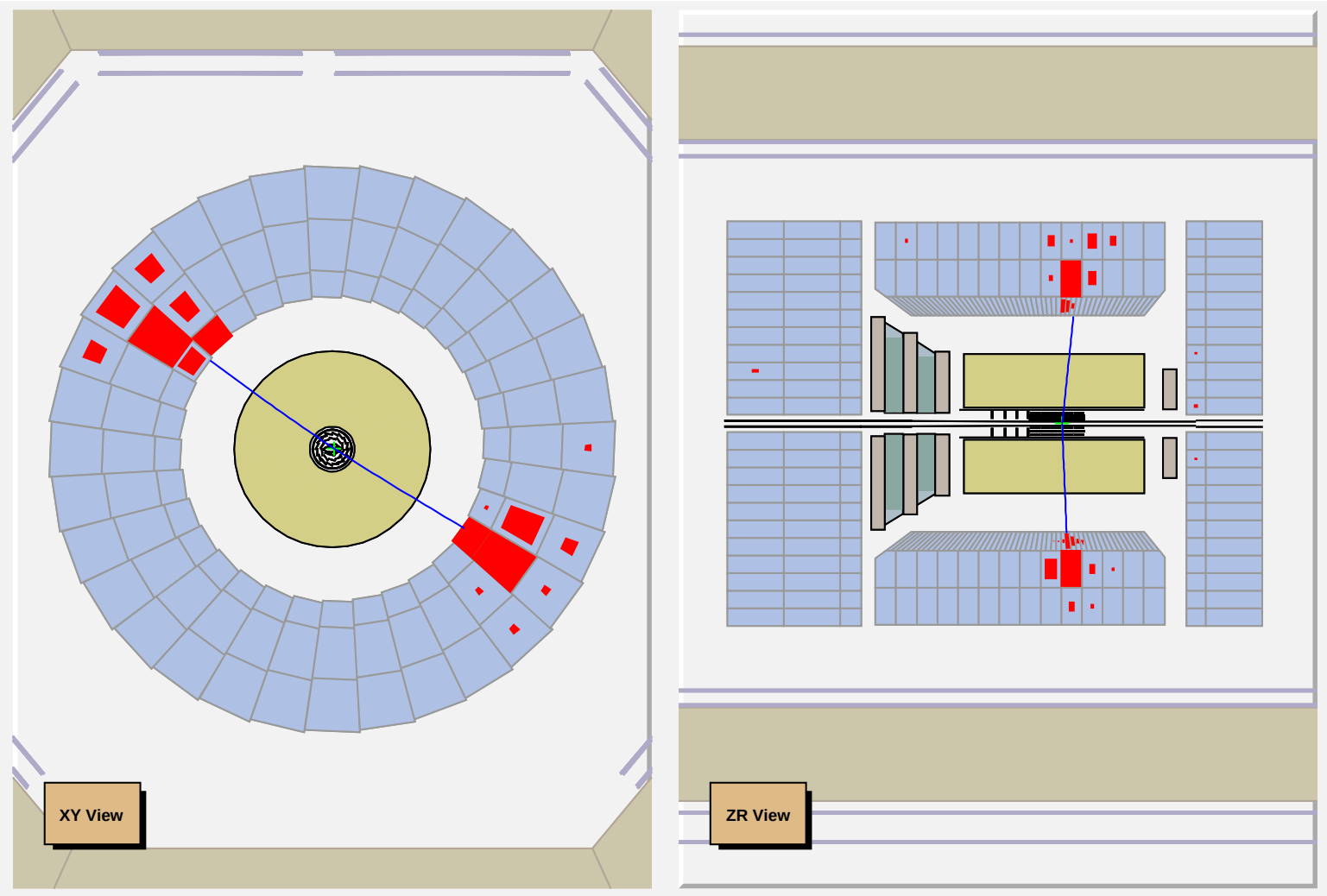
ZEUS ditau events HERA II data (L=0.36 fb^{-1})

Topology	All	jet-jet	e-jet-jet	e-jet	e-e-jet
D cut		0.80	0.50	0.90	0.90
Data	21	14	3	4	0
Total SM	$27.2^{+7.1}_{-6.3}$	$20.2^{+6.8}_{-5.7}$	$1.4^{+3.3}_{-0.2}$	$4.9^{+3.1}_{-1.3}$	$0.7^{+4.4}_{-0.1}$
ditau MC	$13.2^{+0.6}_{-1.0}$	$9.1^{+0.4}_{-0.8}$	1.4 ± 0.1	$2.2 \pm +0.1$	0.5 ± 0.1
(purity)	(49%)	(45%)	(97%)	(46%)	(74%)



Data are in reasonable agreement with SM expectation.

The highest $M_{\tau\tau}^{visible}$ event ($M_{\tau\tau}^{visible}$=40 GeV)



$\tau^+\tau^-$ pair–production @ H1

$ep \to \tau^+\tau^-(ep)$ HERA–I $e^{\pm}p$ data **L=106 pb^{-1}**

Eur. Phys. J. C48 (2006) 699–714

look for all topologies to be able to identify $\tau^+\tau^-$ events

- leptonic(eμ), semi–leptonic(e–jet, μ–jet), hadronic(jet–jet) decay
- look at the jets from low P_T
  - exactly required 1 or 3–tracks in the jet
  - using neural network to identify τ–jet
- the first measurement of $\tau^+\tau^-$ cross section at *ep*–collider

Neural Network based tau–ID

had τ–ID

- To distinguish hadronic 1–prong, 3–prong τ decays from quark/gluon jets ($L_{1-prong}$, $L_{3-prong}$)
- To distinguish hadronic 1–prong τ decays from misidentified electrons/muons (L_{veto}^{e}, L_{veto}^{μ})
  – multiplicities of neutral clusters / invariant mass / number of tracks / 1st moment of energy deposits…

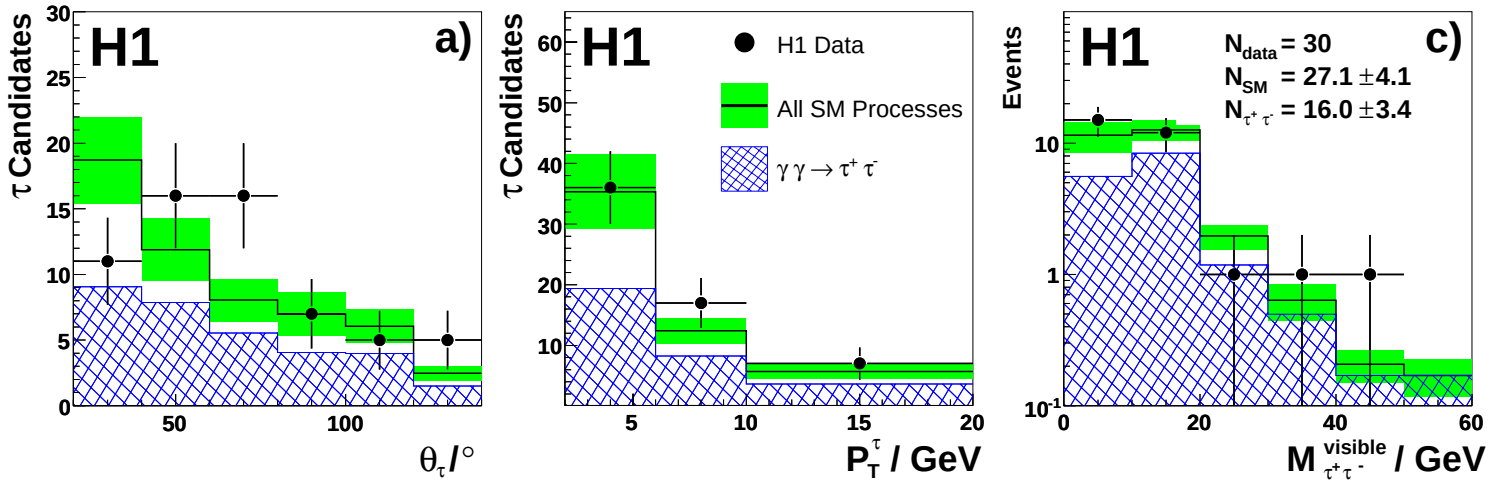
electron	muon	jet
$p_T^e > 3$ GeV	$p_T^\mu > 2$ GeV	**$p_T^{jet} > 2$ GeV** $L_{1-prong} \| L_{3-prong} > 0.75$
Two isolated e or μ or jets of opposite charges		
elastic requirements : No additional tracks/clusters, No activity in forward regions NC/di–e/di–μ rejection : E–Pz < 50 GeV, $L_{veto}^{e} > 0.75$, $L_{veto}^{\mu} > 0.75$		

signal efficiency = 50%
misideintifed probability = 0.5% (4%)

Results of $\tau^+\tau^-$ pair–production @ H1

$ep \to \tau^+\tau^-(ep)$ HERA–I $e^{\pm}p$ data **L=106 pb^{-1}**

Eur. Phys. J. C48 (2006) 699–714



$\tau^+\tau^-$ Results					
Decay Channel	**Leptonic**	**Semi–leptonic**		**Hadronic**	**Total**
	$e\,\mu$	$e\,\tau$–jet	$\mu\,\tau$–jet	τ–jet τ–jet	
H1 Data	7	2	10	11	30
SM	2.9 ± 0.4	6.3 ± 0.9	7.0 ± 1.3	11.0 ± 2.0	27.1 ± 4.1
$\tau^+\tau^-$	56%	47%	85%	50%	59%

Purest final state

Phase space definition

elastic events with two τ leptons of
- $p_T^{\tau} > 2$ GeV
- $20^o < \theta_{\tau} < 140^o$

(acceptance ≈ 1%)

$\sigma_{measured} = 13.6 \pm 4.4_{stat.} \pm 3.7_{syst.}$ pb **first measurement at HERA !!**

$\sigma_{theory} = 11.2 \pm 0.3$ pb (GRAPE)

⟶ good agreement with SM expectation!

$\tau^+\tau^-$ candidate @ H1

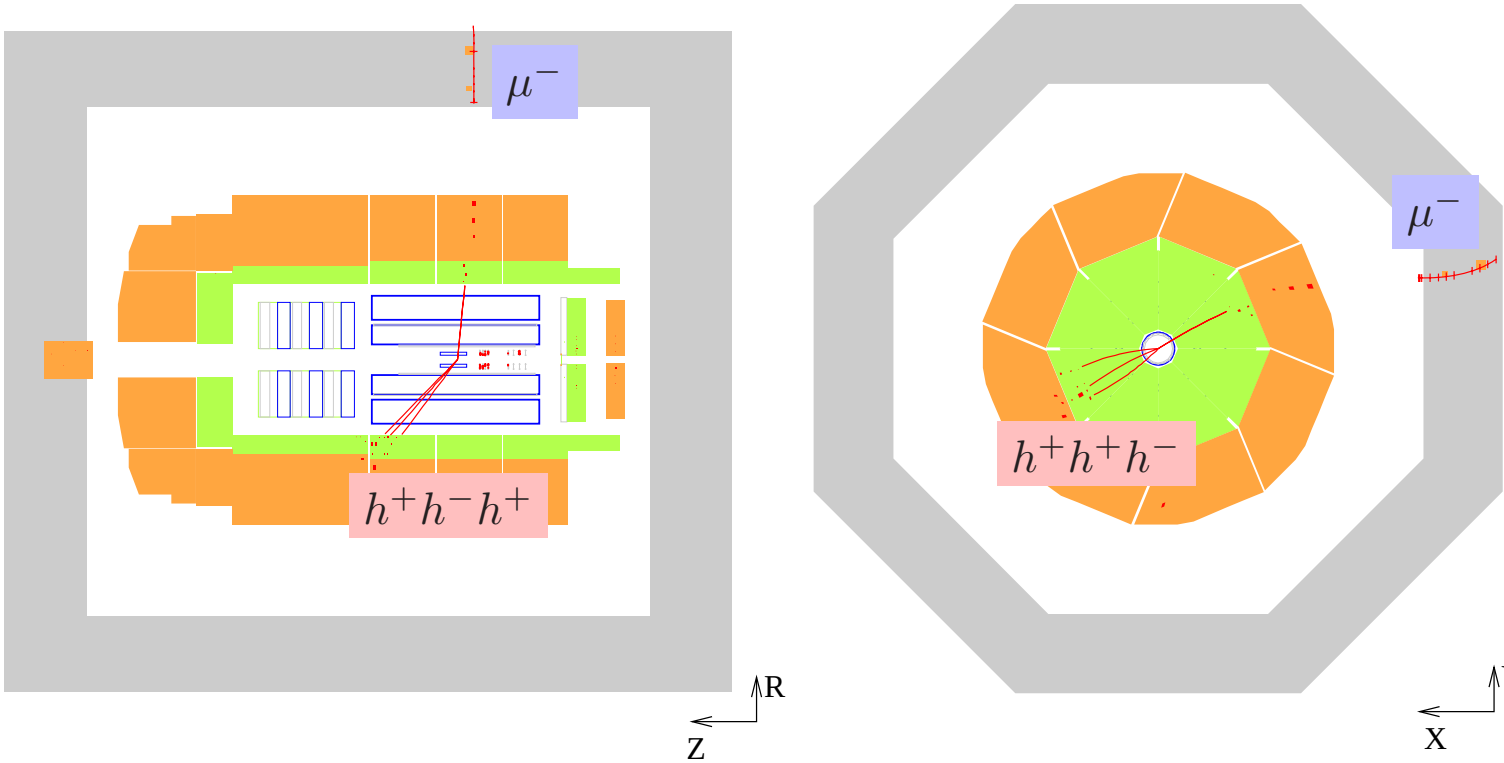
Eur. Phys. J. C48 (2006) 699–714

H1

TAU PAIR CANDIDATE

$$e^+p \longrightarrow e^+ \quad \tau^- \quad \tau^+p$$

$$\mu^- \quad \bar{\nu}_\mu\nu_\tau \qquad h^+h^+h^- \quad \bar{\nu}_\tau$$



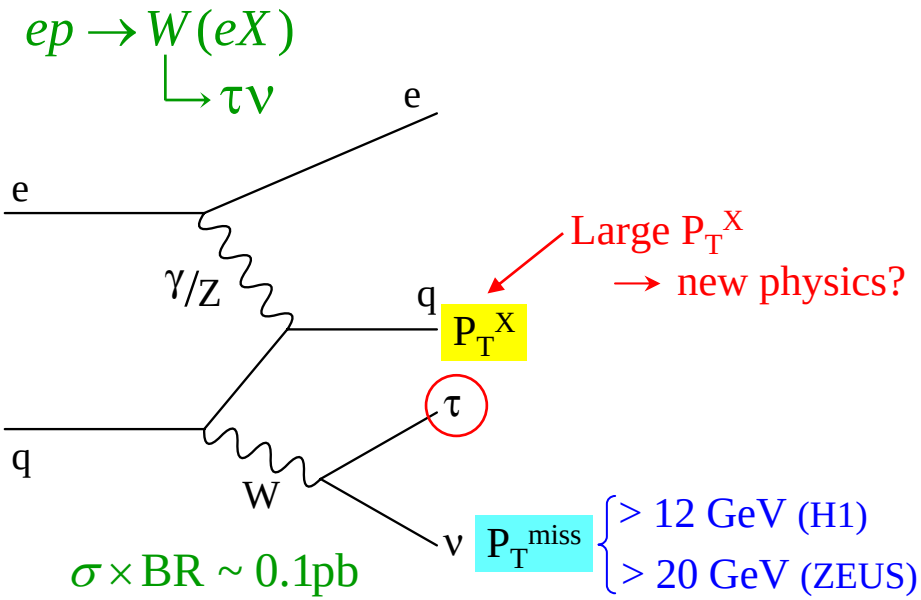
Tau Production at HERA

- $\tau^+\tau^-$ pair–production events
- Isolated τ lepton with missing transverse momentum(P_T^{miss}) events
- Double charged Higgs Search
- Lepton Flavour Violation

Isolated tau leptons + P_T^{miss} physics

ZEUS : Phys. Lett. B 583 (2004) 41

H1 : H1prelim–07–064



Rare process, but sensitive to new physics

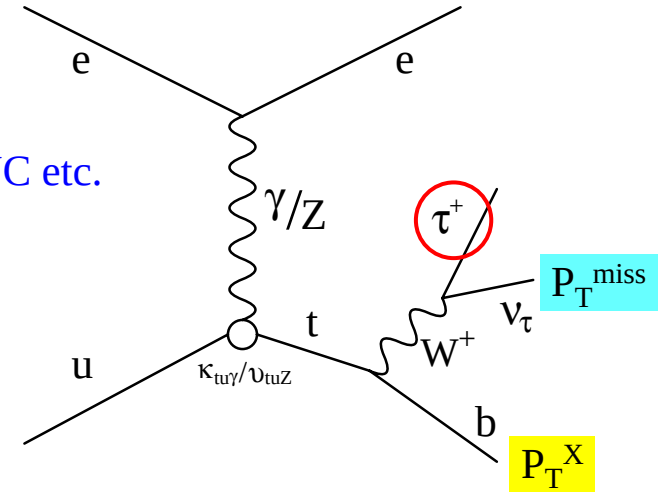
– SM signal is single W boson production with subsequent decay W→ τν.

– Main background is CC events with narrow jets.

– A complement to isolated e(μ) + P_T^{miss} analysis (There is a slight excess for e(μ) channel at H1.)

An excess at high p_T^X could be a sign of new physics.

→ single top production via FCNC etc.



Additional high p_T jet

τ–ID for Isolated τ + P_T^{miss} analysis @ ZEUS

HERA–I $e^{\pm}p$ data **L=130 pb^{-1}**

Phys. Lett. B 583 (2004) 41

had τ–ID

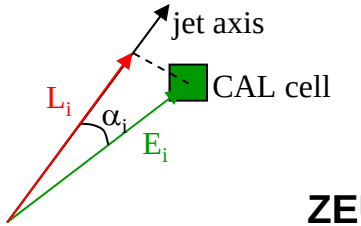
τ–ID using PDE Range Searching

– Same method as $\tau^+\tau^-$ analysis. (see above)

– Variable set is different.

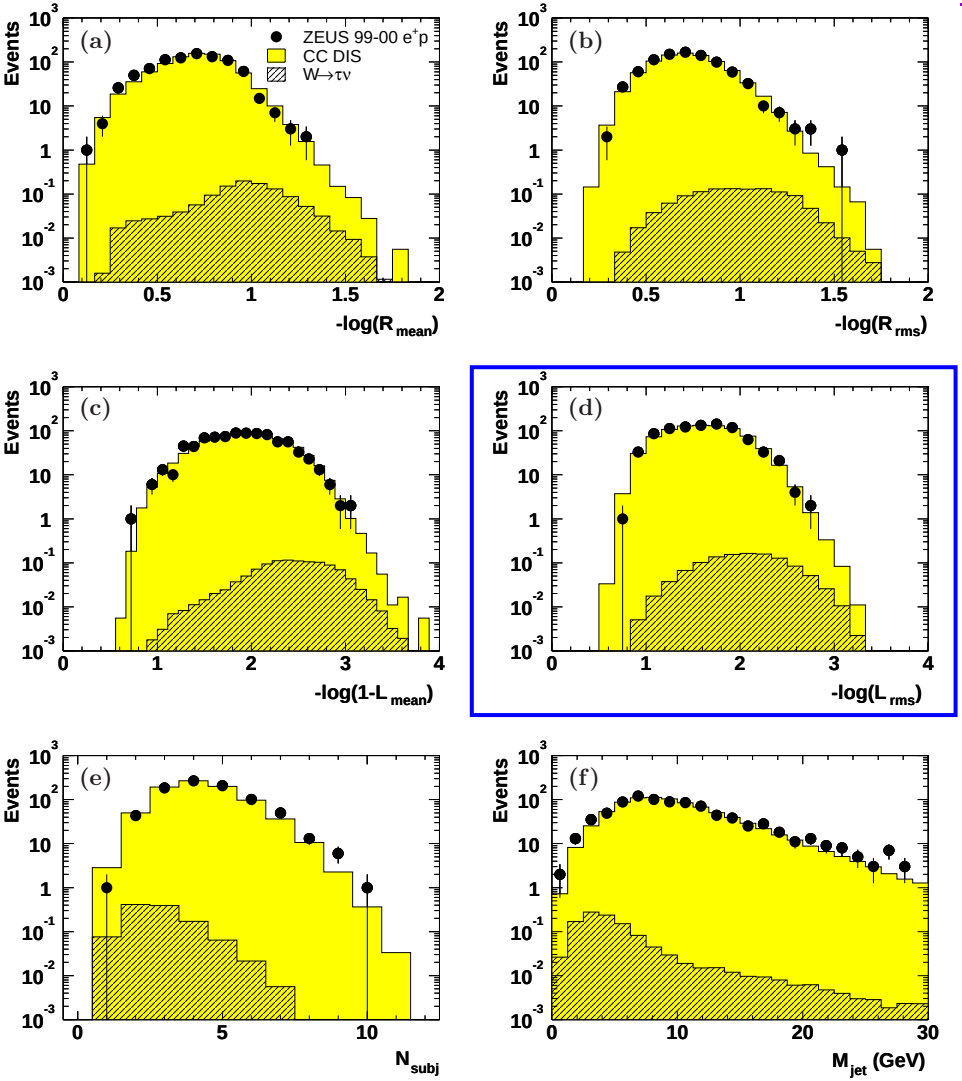
$\log(R_{trk}) \longrightarrow -\log(L_{rms})$

L_{rms} : 2nd moment of longitudinal extension

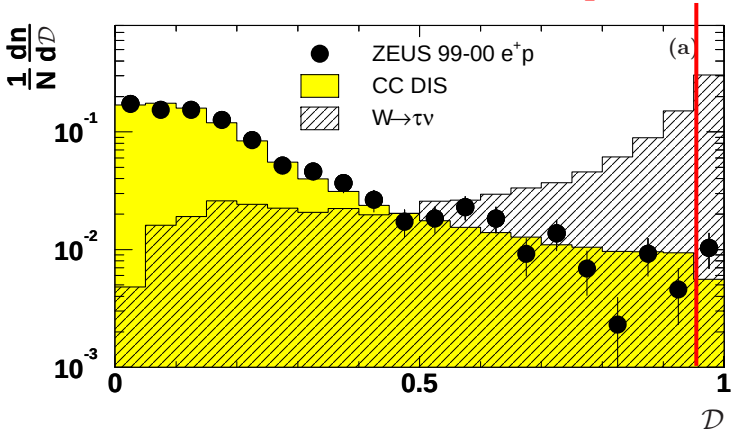


$$Lrms = \sqrt{\frac{\sum_i E_i \left(Lmean - \cos\alpha_i\right)^2}{\sum_i E_i}}$$

ZEUS



required D > 0.95



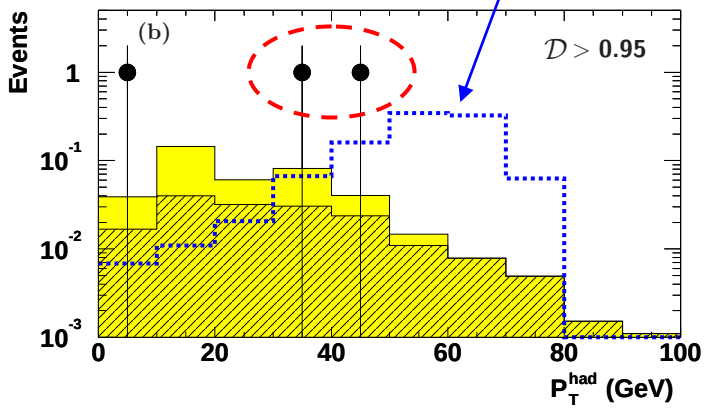
Good separation of signal from background!

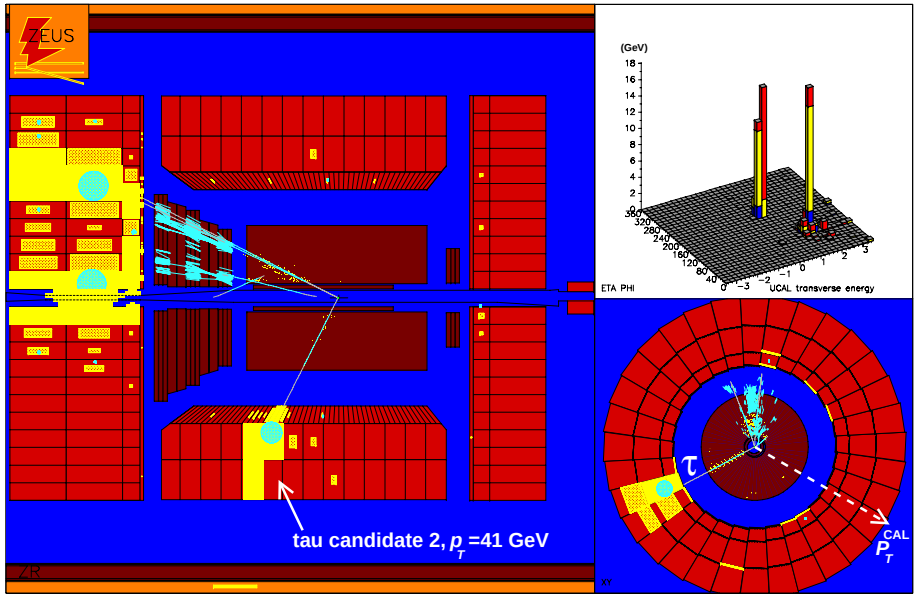
Result of isolated τ + P_T^{miss} @ ZEUS

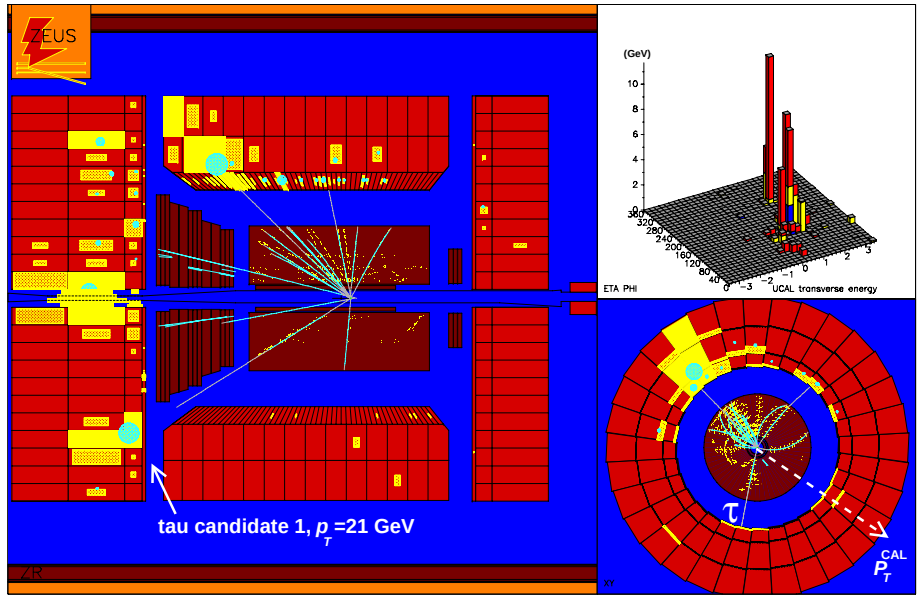
Phys. Lett. B 583 (2004) 41

Interesting τ+P_T^{miss} events at large P_T^X are observed at ZEUS!

ZEUS 1994–2000 $e^{\pm}p$ $L = 130.1\ pb^{-1}$	ZEUS data	SM expectation	$W \rightarrow \tau\nu$ Contribution
Total	**3**	$0.40\ ^{+0.12}_{-0.13}$	43%
$P_T^{had} > 25$ GeV	**2**	0.20 ± 0.05	49%
$p_T^{had} > 40$ GeV	**1**	0.07 ± 0.01	71%







Isolated tau leptons + P_T^{miss} @ H1

H1prelim–07–064

$ep \to W(eX)$, $W \to \tau\nu$

- ZEUS HERA–I result has a slight excess for $\tau + P_T^{miss}$ events.
- H1 analyzed all HERA data. ⟶ **471 pb^{-1}**

cut–based tau–ID

had τ–ID

- look for jet in LAr calorimeter (cone radius = 1.0)

  $P_T^{jet} > 7$ GeV, $20^o < \theta^{jet} < 120^o$

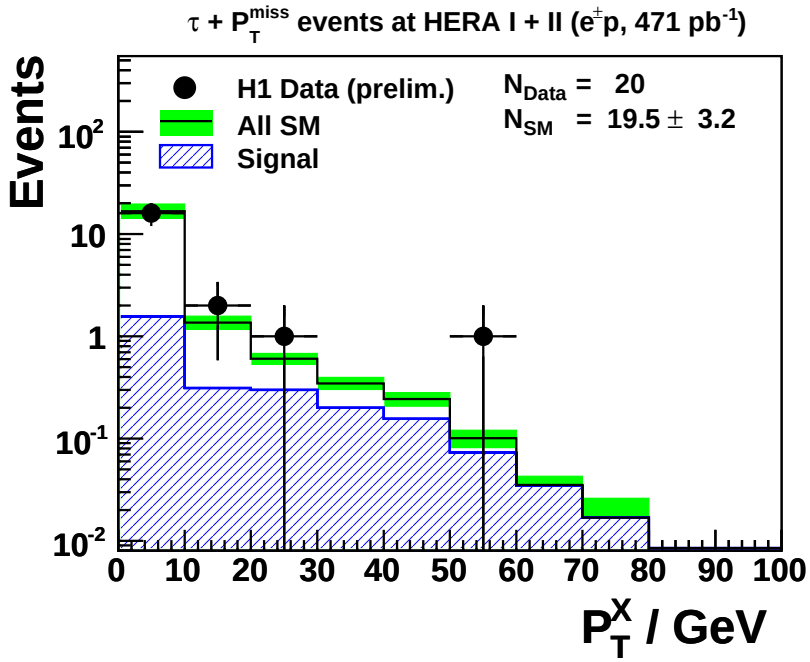
- Isolation : Distance to other e, μ, jet in η–ϕ > 1.0

Radial shower shape ("Jet radius") **< 0.12**

$$R_{jet} = \frac{1}{E_{jet}} \sum_h E_h \sqrt{\Delta\eta(jet,h)^2 + \Delta\phi(jet,h)^2}$$

- $N_{jet}^{tracks} = 1$ (only 1–prong jet)

⟶ misidentification probability : **< 1%**



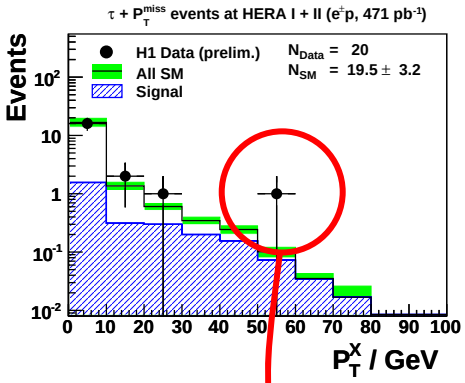
H1 Preliminary τ+P_T^{miss} events at HERA I+II		H1 Data	SM Expectation	SM Signal $W \to \tau\nu$	Other SM Processes
$e^{\pm}p$ 471 pb^{-1}	Full Sample	20	19.5 ± 3.2	2.7 ± 0.4	16.8 ± 2.8
	$P_T^X > 25$ GeV	1	0.99 ± 0.13	0.62 ± 0.10	0.37 ± 0.03

CC events are dominant.

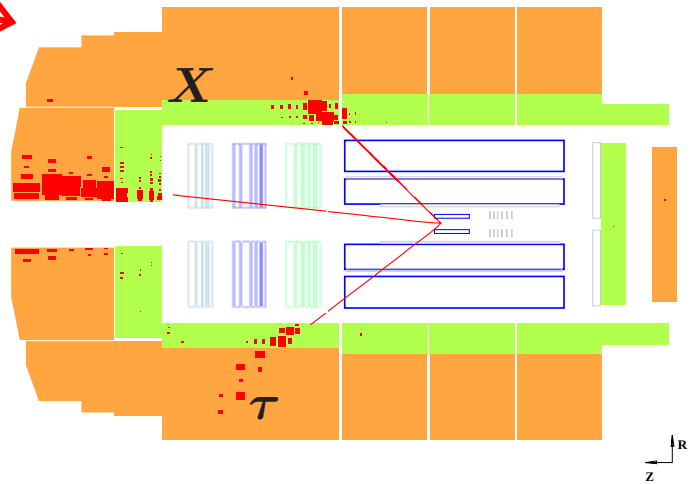
Data in good agreement with SM prediction!

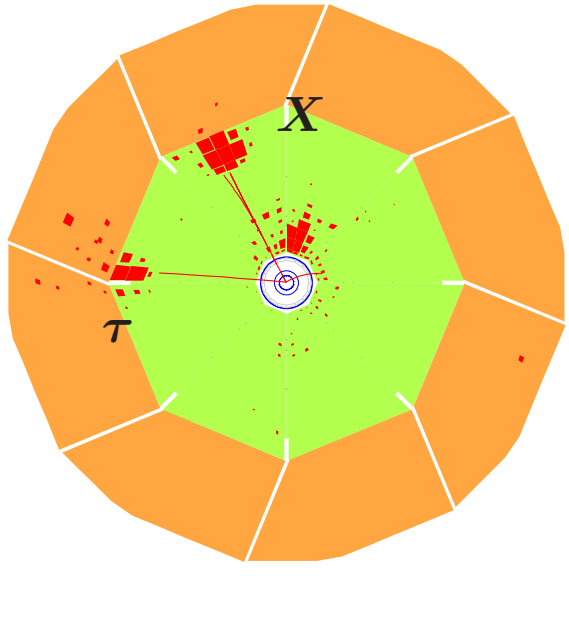
τ + P_T^{miss} candidate event

H1prelim–07–064



H1 $\tau + P_T^{miss}$ candidate with large P_T^X





$P_T^{miss} = 59$ GeV $\quad P_T^{\tau} = 14$ GeV $\quad P_T^X = 51$ GeV

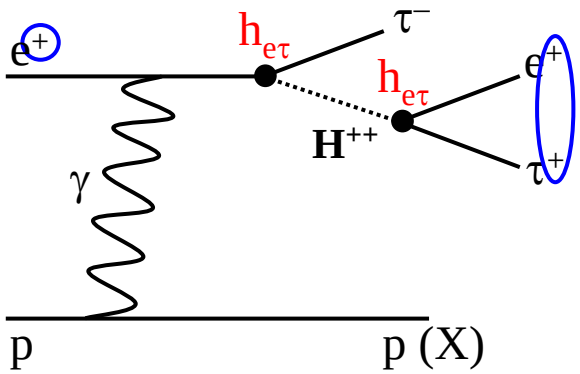
Tau Production at HERA

- $\tau^+\tau^-$ pair–production events
- Isolated τ lepton with missing transverse momentum(P_T^{miss}) events
- Double charged Higgs Search
- Lepton Flavour Violation

Doubly–charged Higgs search @ H1

searched for H^{++} bosons using HERA–I e^+p data **L=88 pb^{-1}**

Phys. Lett. B 638 (2006) 432



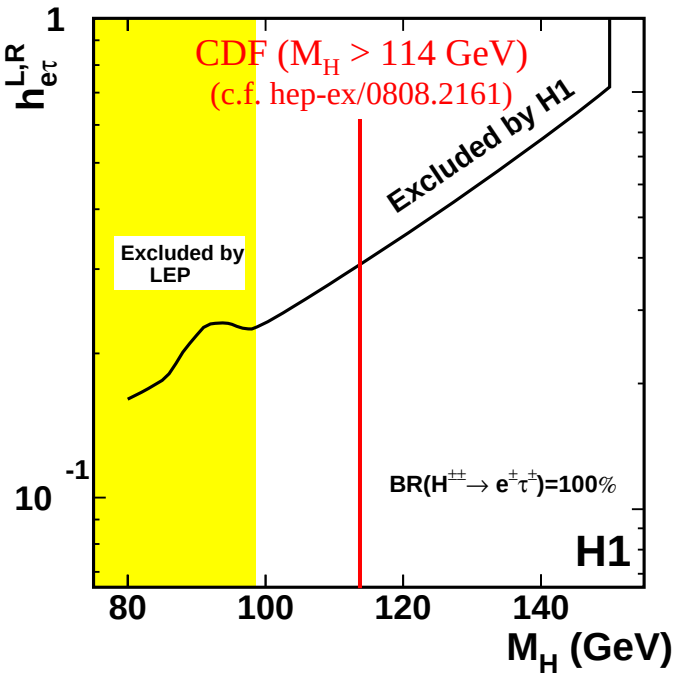
Event class	$H^{++} \to e^+\tau^+$ final selection		
	N_{obs}	N_{bckg}	Signal fraction
$e\mu$	0	0.27 ± 0.02	6 %
eh	1	1.66 ± 0.48	12 %
ee	0	0.14 ± 0.04	7 %
total	1	2.07 ± 0.54	25 %

SM signal efficiency

had τ–ID

cut–based tau–ID

e	μ	jet
p_T^e > 10(5) GeV Isolated	p_T^μ > 10(5) GeV Isolated	p_T^{jet} > 10(5) GeV
		No other track within 0.15 < R < 1.5
P_T^{miss} > 8 GeV (*e–e*) / P_T^{miss} > 11 GeV (*e–jet*)		
Charge of Higgs decay product candidates = lepton beam charge		



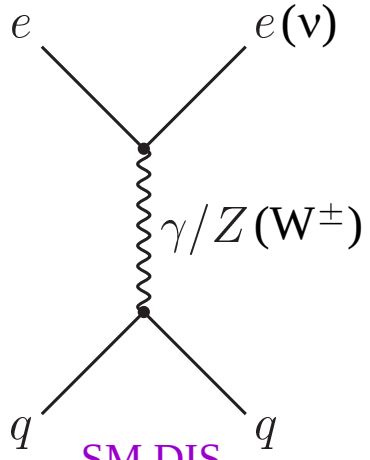
No evidence for $H^{++} \to e^+\tau^+$ decays

Lepton Flavour Violation @ H1/ZEUS

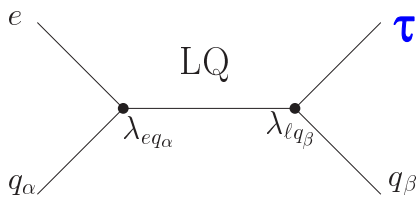
searched for Lepton Flavour Violation

H1 : Eur. Phys. J. C52 (2007) 833–847

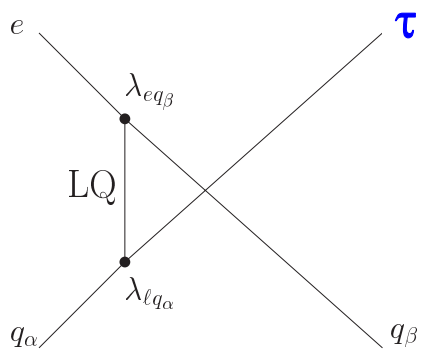
ZEUS : Eur. Phys. J. C44 (2005) 463–479



SM DIS



s–channel



u–channel

Leptoquark(LQ)s couple to both quarks and leptons.

It carries both leptonic(L) and baryonic (B) numbers.

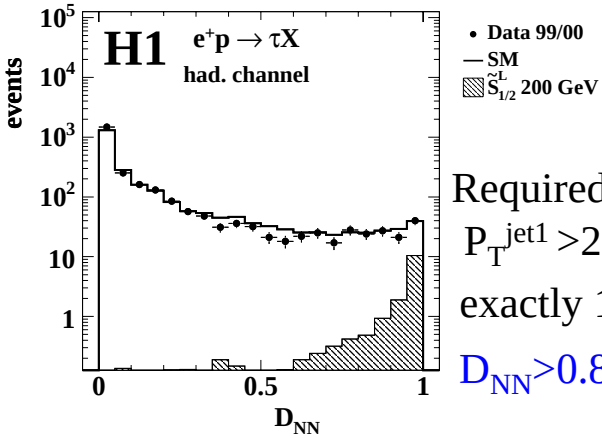
Neural Network based tau–ID

had τ–ID

80% signal efficiency

95% quark/gluon induced jet rejection

like H1 $\tau^+\tau^-$ analysis



Required :

P_T^{jet1} >25GeV, P_T^{jet2} >15GeV

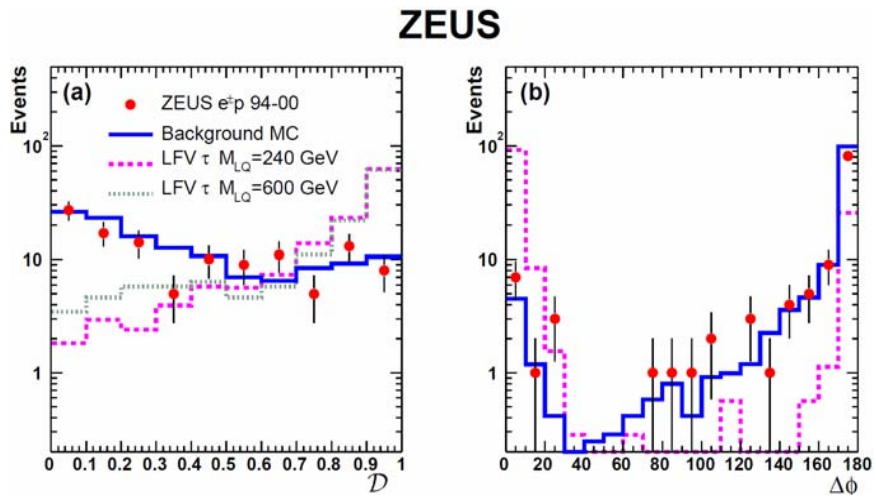
exactly 1 or 3 tracks in the jet

D_{NN}>0.8 & …

τ–ID using PDE Range Searching

had τ–ID

same discriminant as in ZEUS τ+P_T^{miss} search



Limits for LQs in the τ channel @ H1/ZEUS

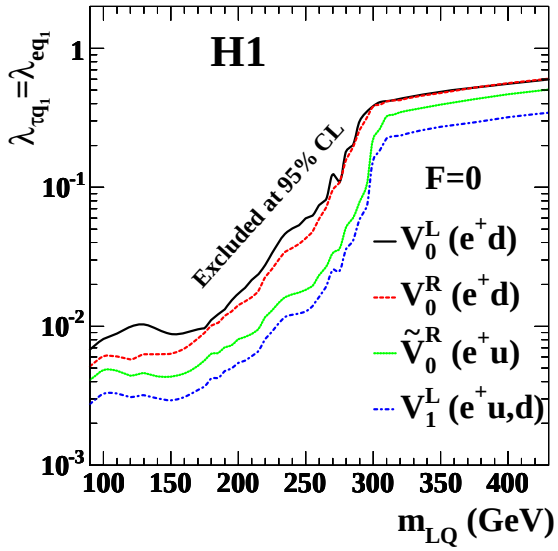
Eur. Phys. J. C52 (2007) 833–847

HERA–I $e^{\pm}p$ data **L=80.2 pb^{-1}**

No significant deviation from SM found.
Limits were set on coupling to LQ
leading to Lepton Flavour Violation.

H1 e^-p: 13.7 pb^{-1}, e^+p: 66.5 pb^{-1}			
		Data	SM MC
$ep \rightarrow \tau X$	e^-p	0	0.75 ± 0.21
	e^+p	1	4.90 ± 0.85

⟶ No evidence for LFV



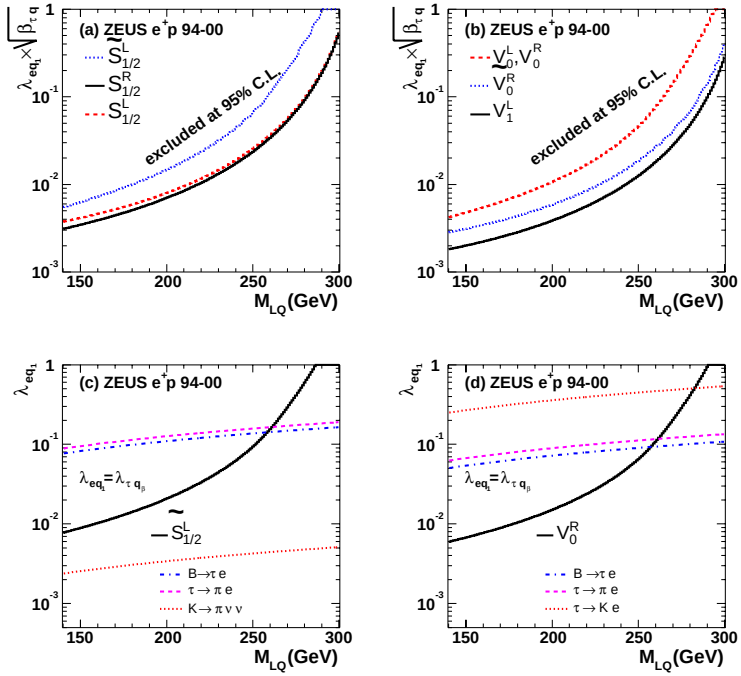
Eur. Phys. J. C44 (2005) 463–479

No candidate was found. Limits on LQ were set.

HERA–I $e^{\pm}p$ data **L=130 pb^{-1}**

Data	0
SM	2.3 ± 0.5
sel. eff.	22~30% ($M_{LQ} < \sqrt{s}$)

ZEUS ⟶ No evidence for LFV



Summary

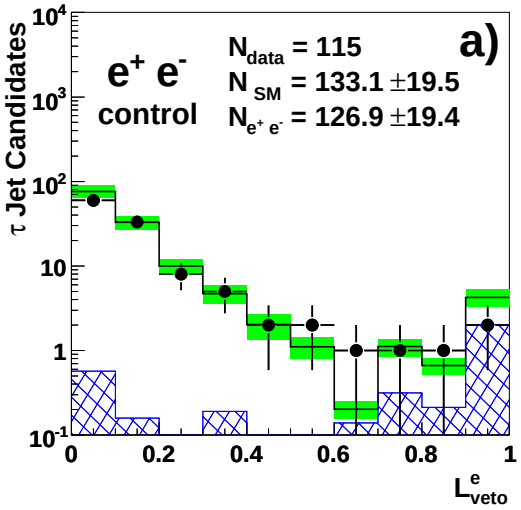
- Only a few taus have been seen at HERA.
  - Detecting taus at HERA is a challenging task.
- They are an important signature for new physics.
- Many tools for the identification of hadronically–decayed taus have been developed by H1 and ZEUS.

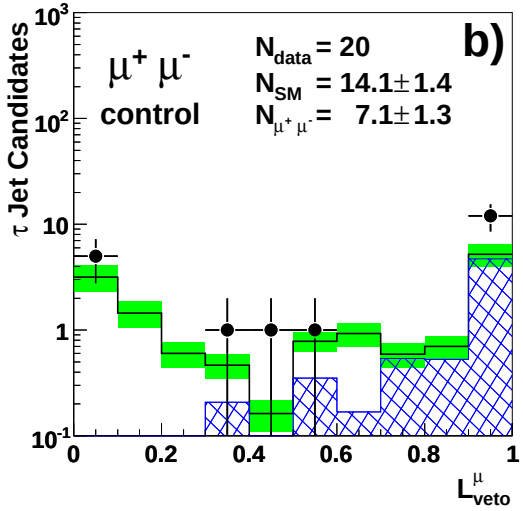
- Results for $\tau^+\tau^-$ pair–production are in agreement with SM prediction (H1/ZEUS).
- New result of isolated $\tau + P_T^{miss}$ from H1 is in agreement with SM expectation.
  - ZEUS result using HERA–I data has a slight excess.
- No evidence for $H^{++} \rightarrow e^+\tau^+$ decays (H1) and lepton flavour violation (H1/ZEUS)

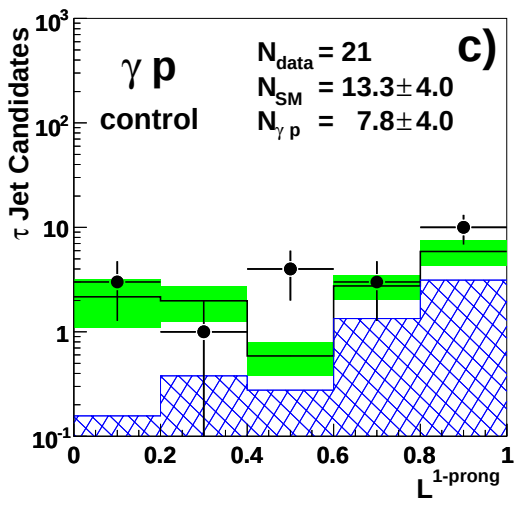
- HERA data taking ended on June 30 2007 after 15 years successful operation:
  - Each experiment has collected ~500 pb^{-1} data.
  - Tau analyses have not finalized yet, still more to come for the next years!

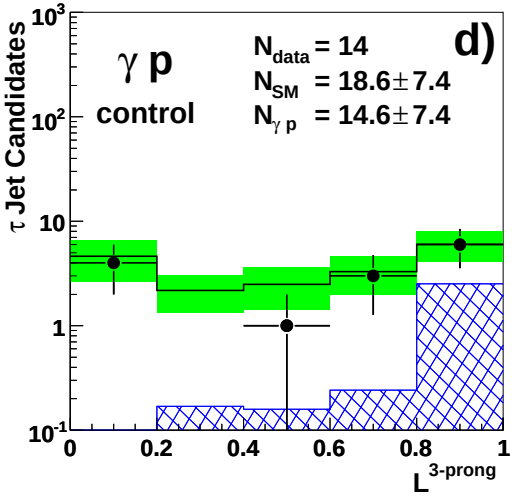
backup slides

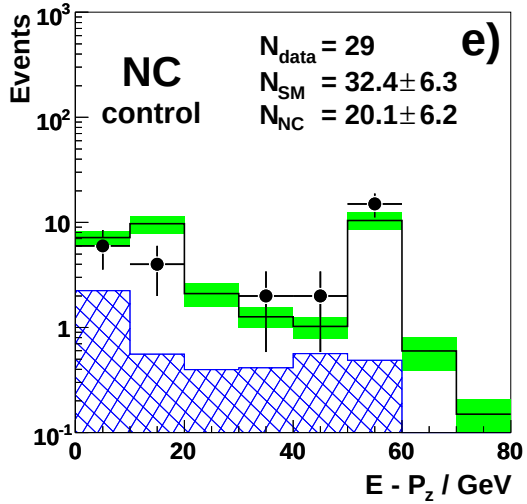
Background control sample for $\tau^+\tau^-$ pair–production @ H1

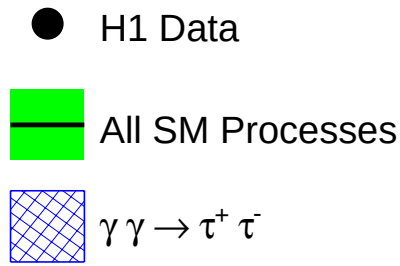












Event selection for isolated tau + P_T^{miss} @ H1

H1prelim–07–064

CC selection

$P_T^{miss} > 12$ GeV

the ratio of the anti–parallel and parallel components of the hadronic P_T

Inclusive CC	$P_T^{calo} > 12$ GeV
	$P_T^{had} > 12$ GeV
	$P_T^{miss} > 12$ GeV
	$\delta^{miss} > 5$ GeV
	$V_{ap}/V_p < 0.5$
	(< 0.15 if $P_T^{miss} < 25$ GeV)
Narrow Jets	$P_T^{jet} > 7$ GeV
	$20 < \theta^{jet} < 120$
	$R^{jet} < 0.12$
	$N_{tracks}^{jet} \geq 1$, $\max(P_T^{track}) > 5$ GeV
Isolation	$D_{em,\mu,jet} > 1.0$
Acoplanarity	$\Delta\varphi(\tau, X) < 170$ if $P_T^X > 5$ GeV
1-Prong Jets	$N_{tracks}^{Djet<1.0} = 1$
Final Selection	$N_{\mathrm{DTNV}}^{D_{track}<0.3} = 1$

Tau–jet selection **(cut–based)**

look for jet in LAr calorimeter (cone radius = 1.0)

$P_T^{jet} > 7$ GeV, $20^o < \theta^{jet} < 120^o$

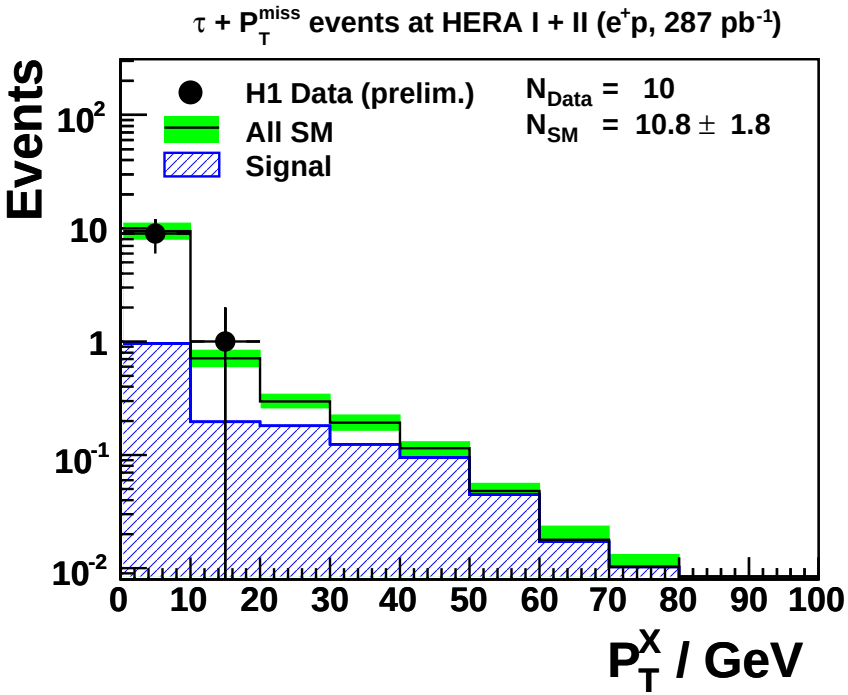
Isolation : Distance to other e, μ, jet in η–ϕ > 1.0

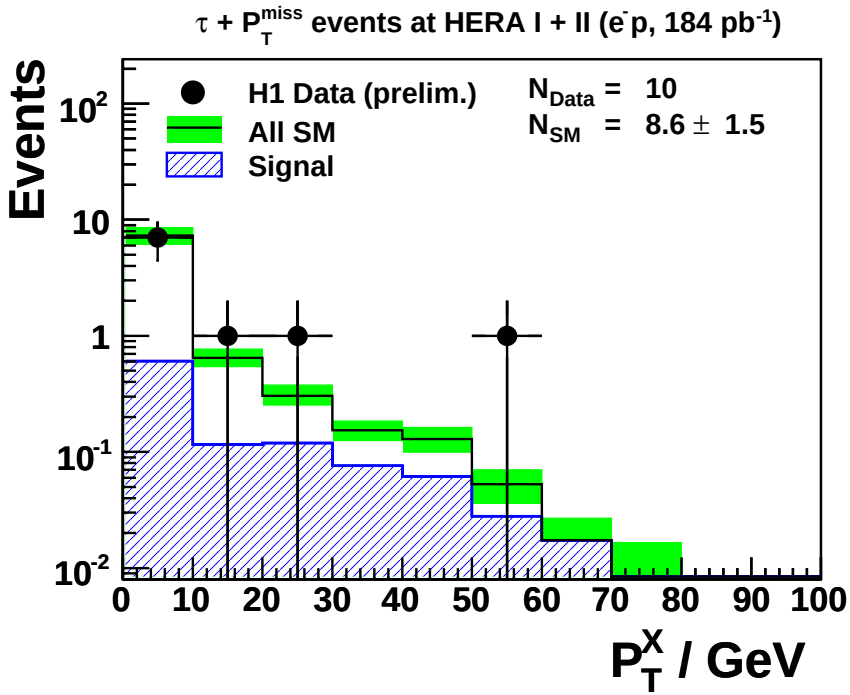
Radial shower shape ("Jet radius")

$$R_{jet} = \frac{1}{E_{jet}} \sum_h E_h \sqrt{\Delta\eta(jet,h)^2 + \Delta\phi(jet,h)^2}$$

only 1–prong jet → (misidentification probability : < 1%)

Isolated tau leptons + P_T^{miss} @ H1

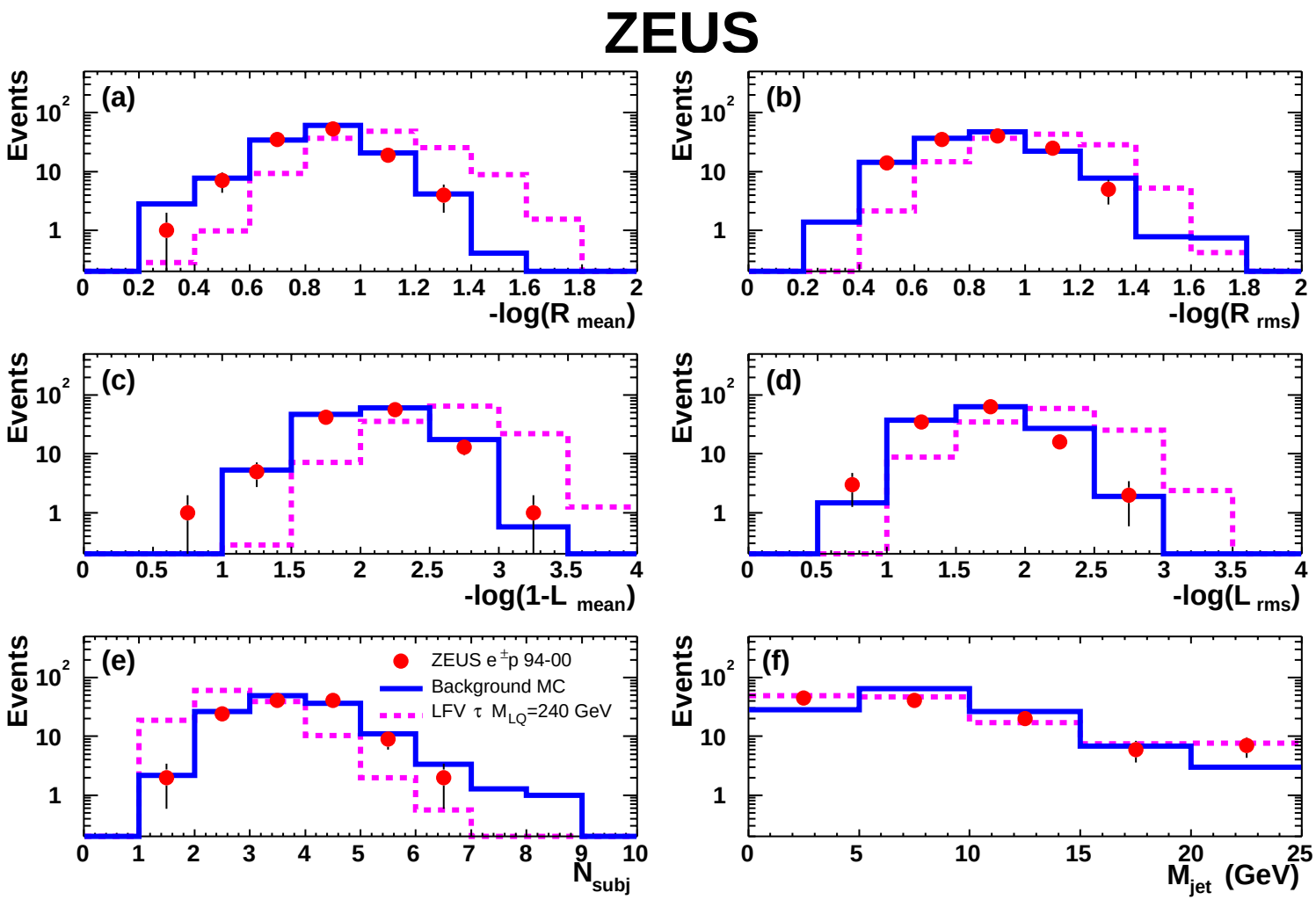




H1 Preliminary τ+P_T^{miss} events at HERA I+II		H1 Data	SM Expectation	SM Signal $W \to \tau\nu$	Other SM Processes
e^+p	Full Sample	10	10.8 ± 1.8	1.6 ± 0.3	9.2 ± 1.6
287 pb^{-1}	$P_T^X > 25$ GeV	0	0.53 ± 0.07	0.38 ± 0.06	0.15 ± 0.01
e^-p	Full Sample	10	8.6 ± 1.5	1.0 ± 0.2	7.6 ± 1.4
184 pb^{-1}	$P_T^X > 25$ GeV	1	0.47 ± 0.07	0.25 ± 0.04	0.22 ± 0.03
$e^\pm p$	Full Sample	20	19.5 ± 3.2	2.7 ± 0.4	16.8 ± 2.8
471 pb^{-1}	$P_T^X > 25$ GeV	1	0.99 ± 0.13	0.62 ± 0.10	0.37 ± 0.03

H1prelim–07–064

Lepton Flavour Violation @ ZEUS



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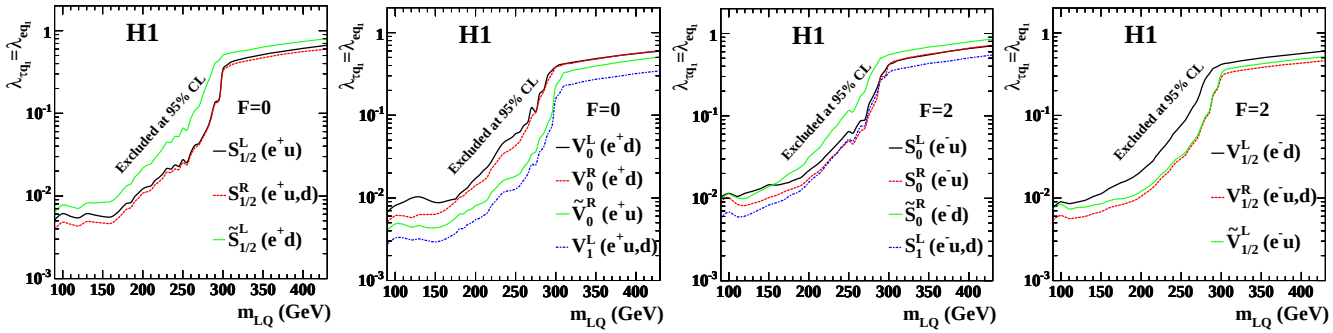
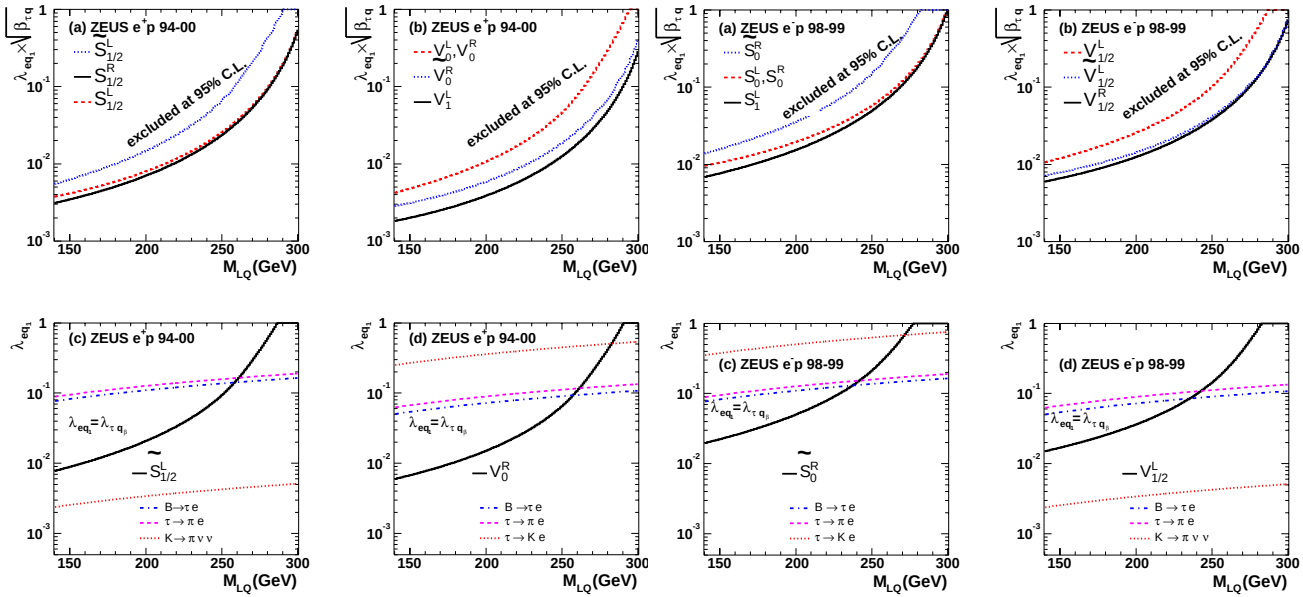


→ No evidence for LFV

ZEUS e^+p data ZEUS e^-p data



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