Università degli Studi di Padova
Dottorato di Ricerca in Fisica – XVI Ciclo

“Search for multi-lepton events with the ZEUS detector at HERA”

and

“VCMVD: an algorithm for MVD tracking at TLT”

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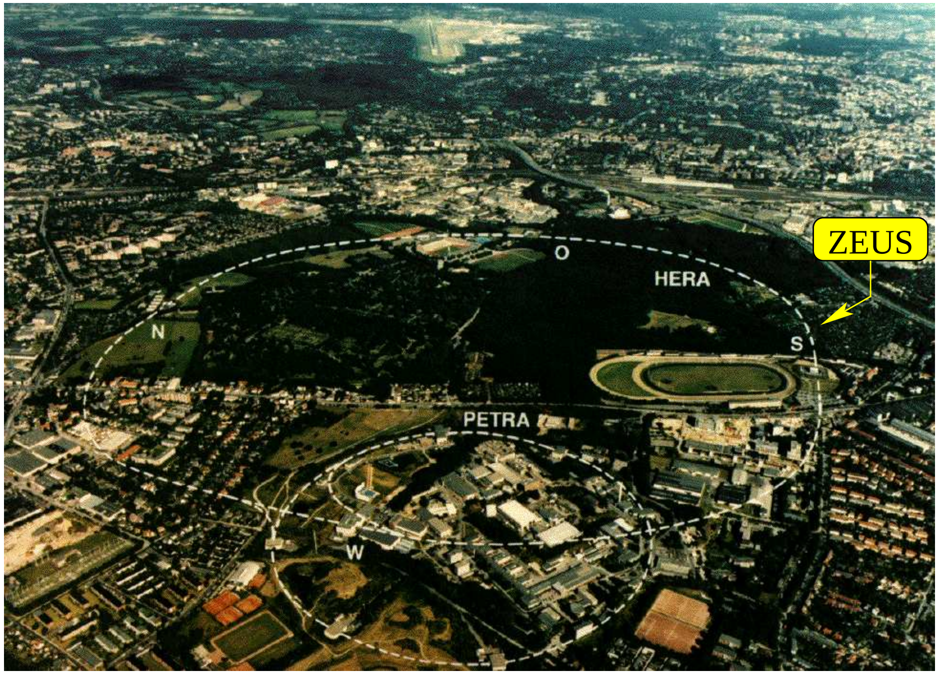
Outline – Part I

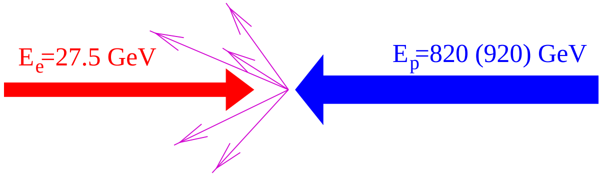
- The experimental setup
- Introduction and motivations
- Multi-electron events search
- Di-muon events search

The HERA Collider

HERA is a particle accelerator located in Hamburg...



...and collides $e^{\pm}p$ at $\sqrt{s}$ = 300/318 GeV:



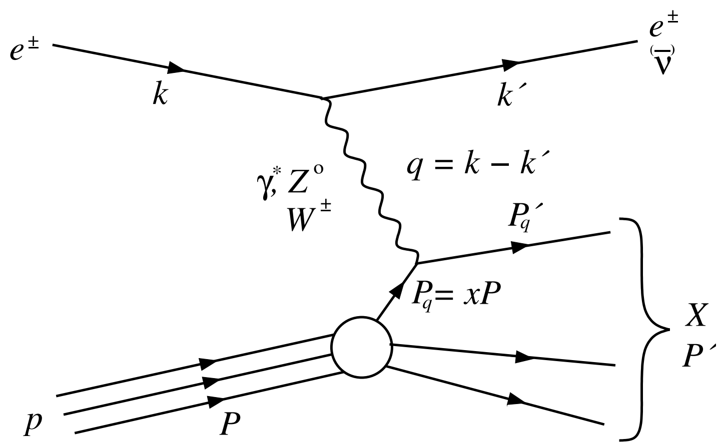
In 1992-2000 HERA supplied the following integrated luminosity:

Years	Lumi [pb^{-1}]	Type
1992-94	2.19	$e^{-}p$
1994-97	70.92	$e^{+}p$
1998-99	25.20	$e^{-}p$
1999-00	94.95	$e^{+}p$

- In 1998 $\sqrt{s}$ was raised from 300 GeV to 318 GeV.

The HERA Collider

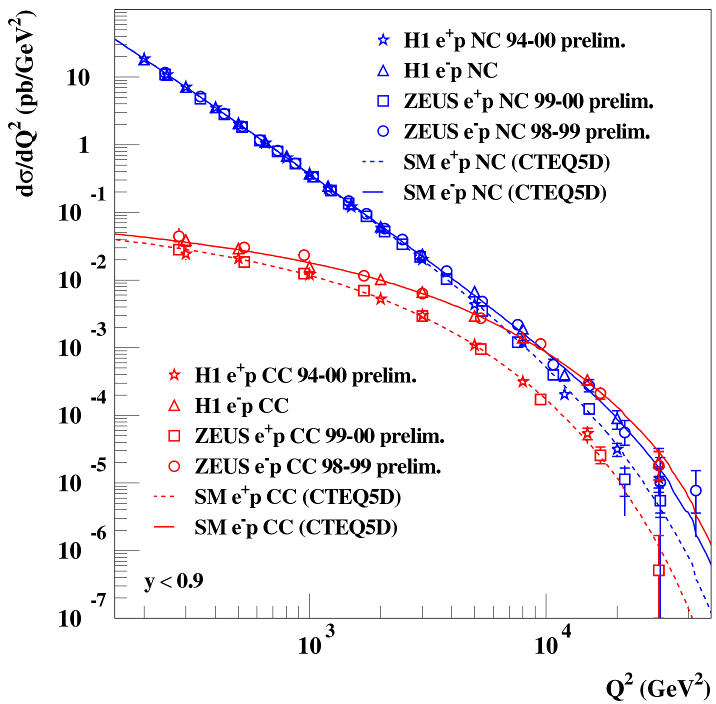
HERA kinematics:



- Centre-of-mass energy: $s = (P + k)^2$.
- Transferred 4-momentum, squared: $Q^2 = -(k - k')^2$.
- Bjorken-x: $x = Q^2/(2P \cdot q)$.
- Inelasticity: $y = (P \cdot q)/(P \cdot k)$.
- Proton-photon mass, squared: $W^2 = (P + q)^2$.

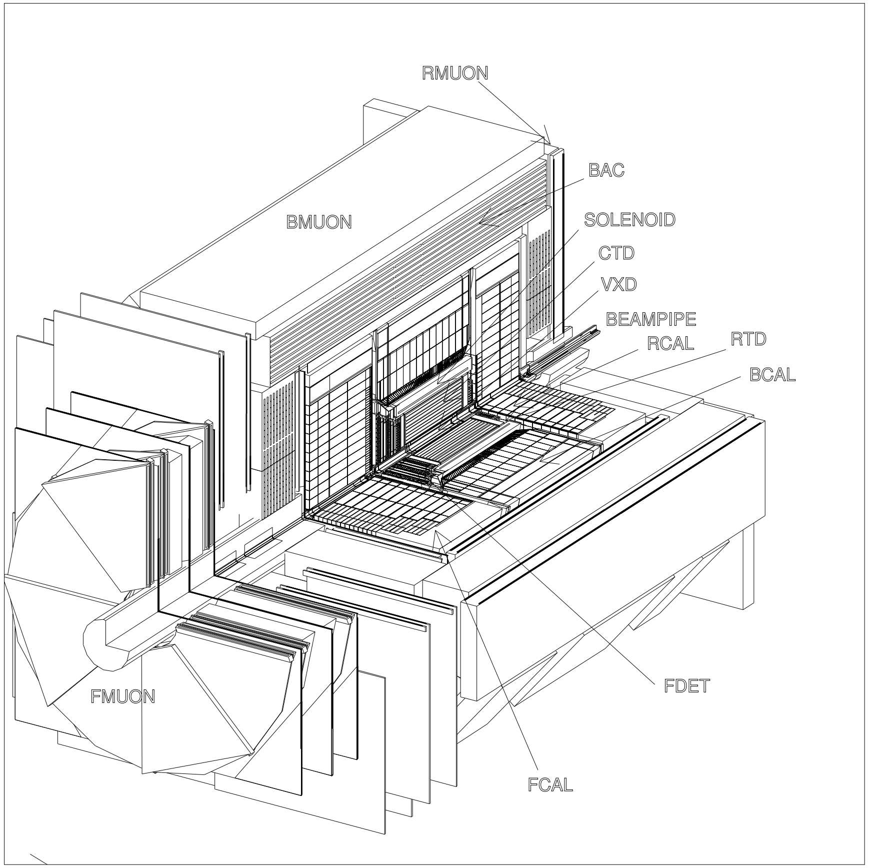
Electron-Proton scattering

- Neutral Current: $ep \to eX$
- Charged Current: $ep \to \nu X$



The ZEUS Detector

ZEUS is a general purpose detector:



The components used in the analyses are:

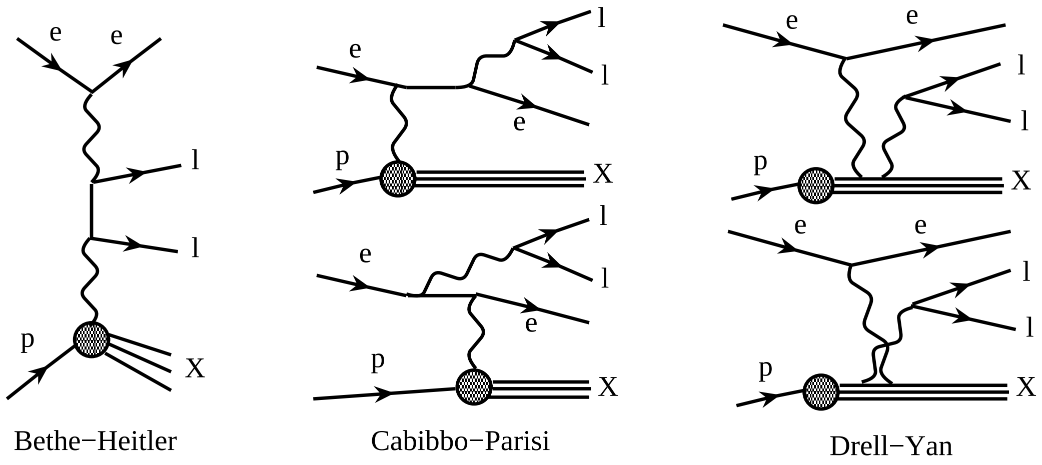
- Central Tracking Detector (CTD),
- Uranium Calorimeter (CAL),
- Muon Chambers (B/RMUON + FMUON),
- Luminosity Monitor.

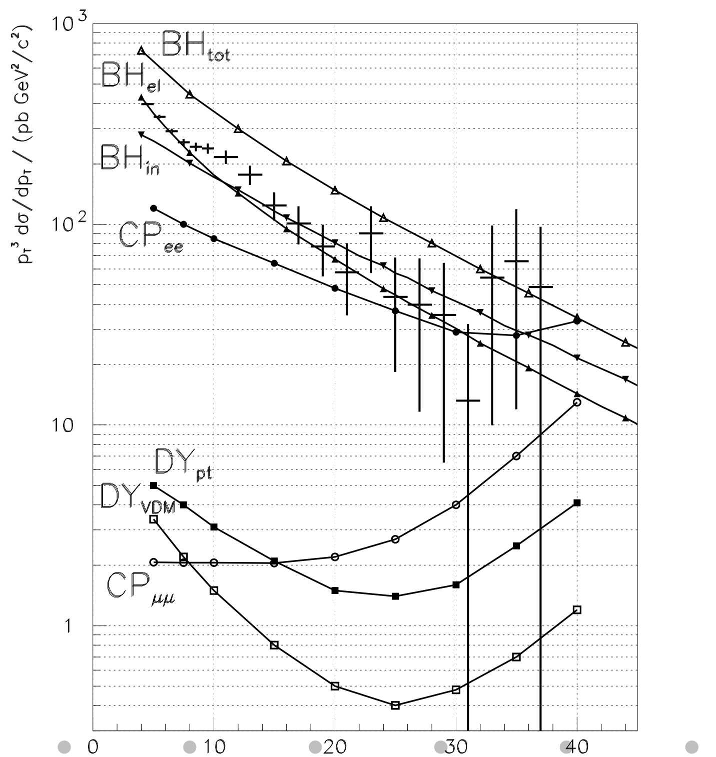
Di-lepton production at HERA

Lepton pair production is a pure QED process, well predictable in the Standard Model (SM) context.

- Main contribution: Bethe-Heitler (BH) process.
- Other contributions: Cabibbo-Parisi (CP) and Drell-Yan (DY).

Feynmann diagrams:





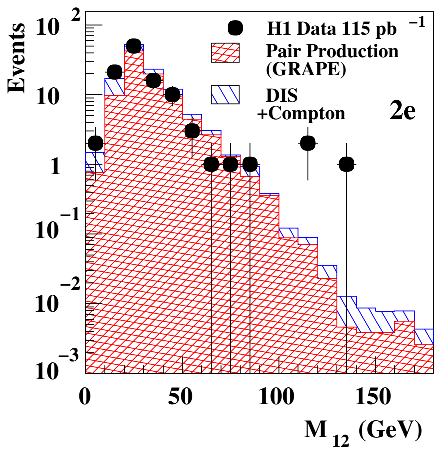
Backgrounds

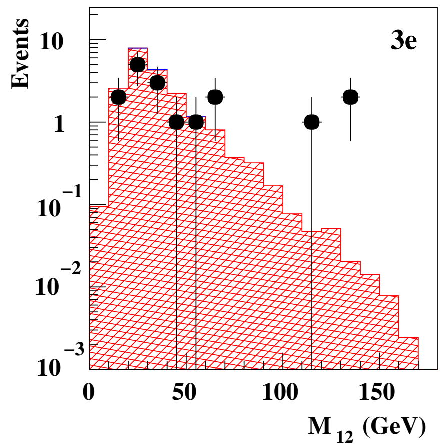
- Vector meson decays: $\Upsilon \longrightarrow l^+l^-$ (BR $\sim$ 1-2%).
- Single lepton production:
  - Heavy quark decays: $q \rightarrow q'W^\star \rightarrow q'l\nu$;
  - W-production;
  - τ decays.
- Backgrounds to multi-electron search: processes where hadrons or photons are misidentified as electrons:
  - Neutral Current DIS;
  - QED-Compton.

Motivations

- Test QED & photon spectrum of the proton.
- Cross-check H1 excesses:

High Mass multi-electrons at H1:

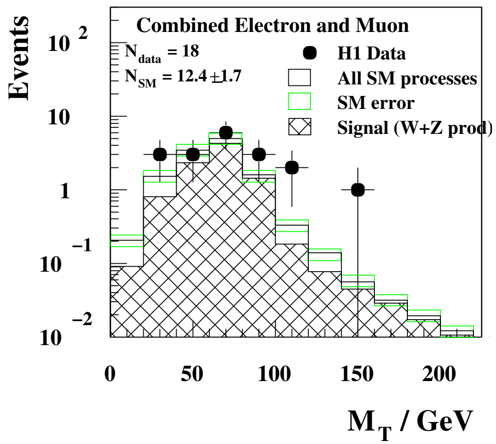




Selection	Data	MC
$2e$, $M_{12} > 100$ GeV	3 evts	0.30±0.04
$3e$, $M_{12} > 100$ GeV	3 evts	0.23±0.04

(see hep-ex/0307015)

Isolated leptons with $\not{P}_T$:

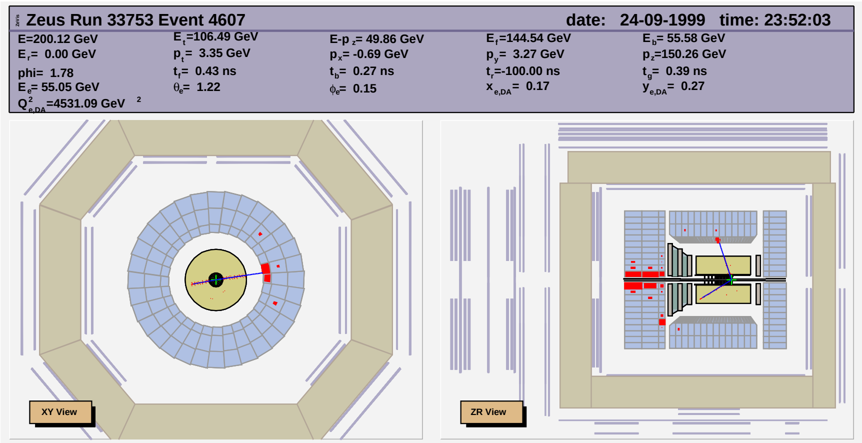


Type	Data	MC
e^+p	$10e$	9.9 ± 1.3
	8μ	2.56 ± 0.44
e^-p	$1e$	1.69 ± 0.22
	0μ	0.37 ± 0.06

(see Phys. Lett. B561, 241)

Multi-electron search

Event Selection



Preselection

Fast selection and reduction of data. Selection criteria:

- Trigger selection: di-electron OR NC-DIS OR High-E_T;
- No. of CTD tracks: $1 \leq N_{\mathrm{TrkVtx}} \leq 9$;
- Transverse momentum in CTD: $\sum_i P_{T,i} > 3$ GeV.

Electron selection

- EM electron finder (CTD+CAL info);
- Isolation cuts:
  - $E_{\mathrm{cone}} < 0.3$ GeV in R=0.3 ($\eta\phi$),
  - $N_{\mathrm{Trk}} = 0$ in R=0.4 ($\eta\phi$);
- $E_e > 10$ GeV ($\theta \leq 164°$) OR $E_e > 5$ GeV ($\theta > 164°$).

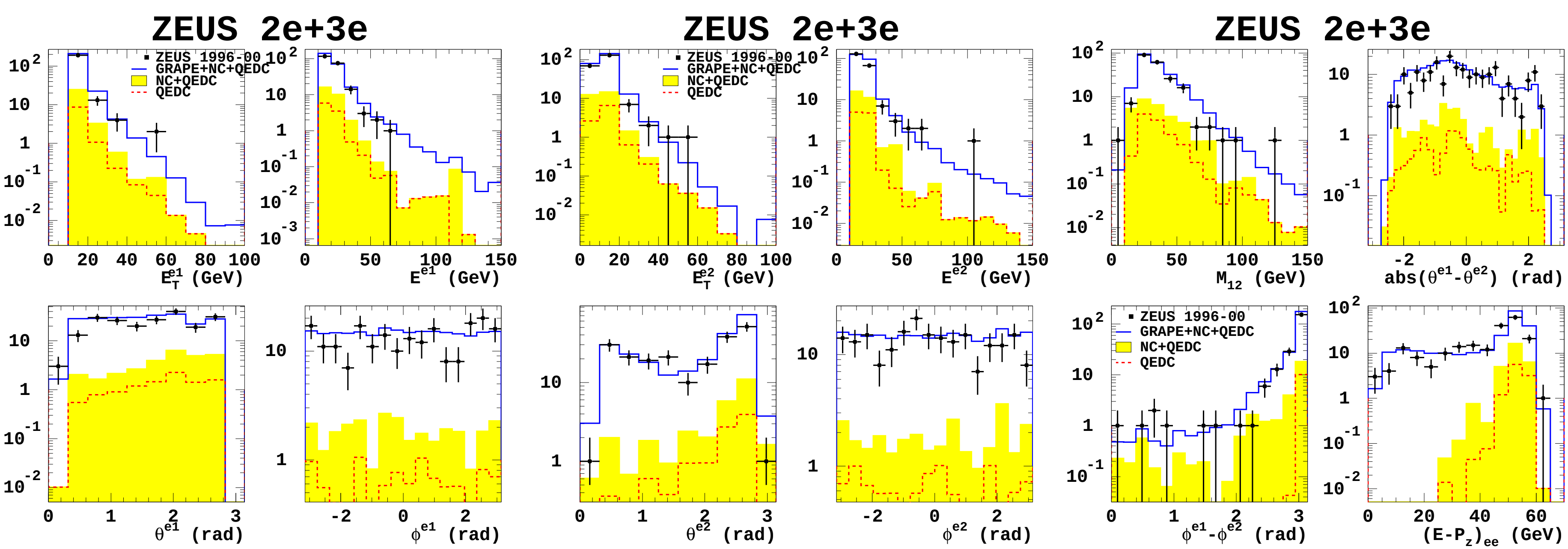
Event Selection

- Vertex: $|z| < 50$ cm;
- two electrons in $17° < \theta < 164°$;
- $E_T^{e1} > 10$ GeV;
- $E_T^{e2} > 5$ GeV.

→ Two classes: "$2e$" (2 electrons) and "$3e$" (3 electrons) events.

Data to MC comparison

1996-2000 data taking ➜ L=120.49 pb^{-1}					
Selection	Data	All SM	di-ele MC	NC-DIS MC	QED-C MC
All $2e$+$3e$	209	235.82	207.00	18.72	10.10
$M_{12} > 50$ GeV	23	35.01	30.14	3.40	1.47
$M_{12} > 100$ GeV	1	1.12	0.91	0.08	0.13



➜ $E - P_z$ permits to separate Bkg from signal.

Monte Carlo describes data reasonably well.

Cross section: sample selection

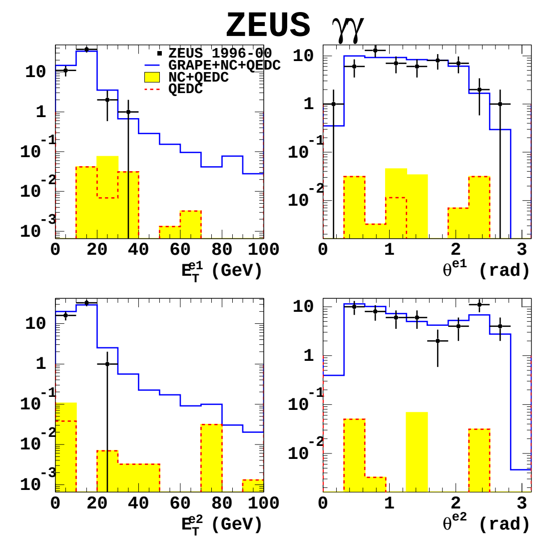
A clean $ep \rightarrow eeX$ sample is needed for cross section measurement.

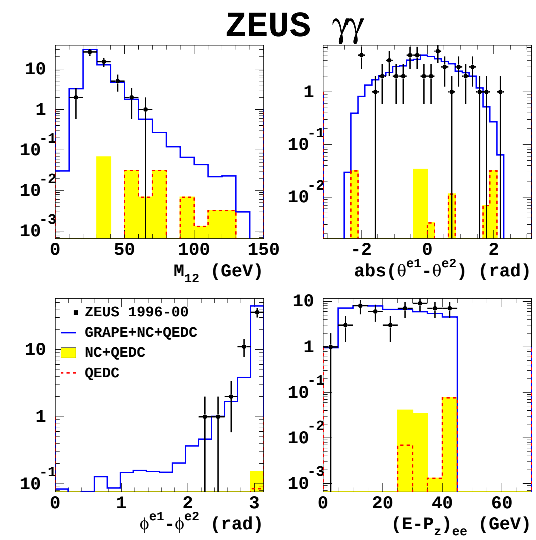
"$\gamma\gamma$" selection

- 2 electrons in $17^\circ < \theta < 164^\circ$;
- $E_T^{e1} > 10$ GeV and $E_T^{e2} > 5$ GeV;
- $M_{12} > 5$ GeV;
- $E - P_z < 45$ GeV (cuts NC-DIS and QED-C).

Results

Selection	Data	All SM	di-ele MC
All $\gamma\gamma$	51	52.86	52.71
$M_{12} > 50$ GeV	3	2.88	2.80
$M_{12} > 100$ GeV	0	0.09	0.08





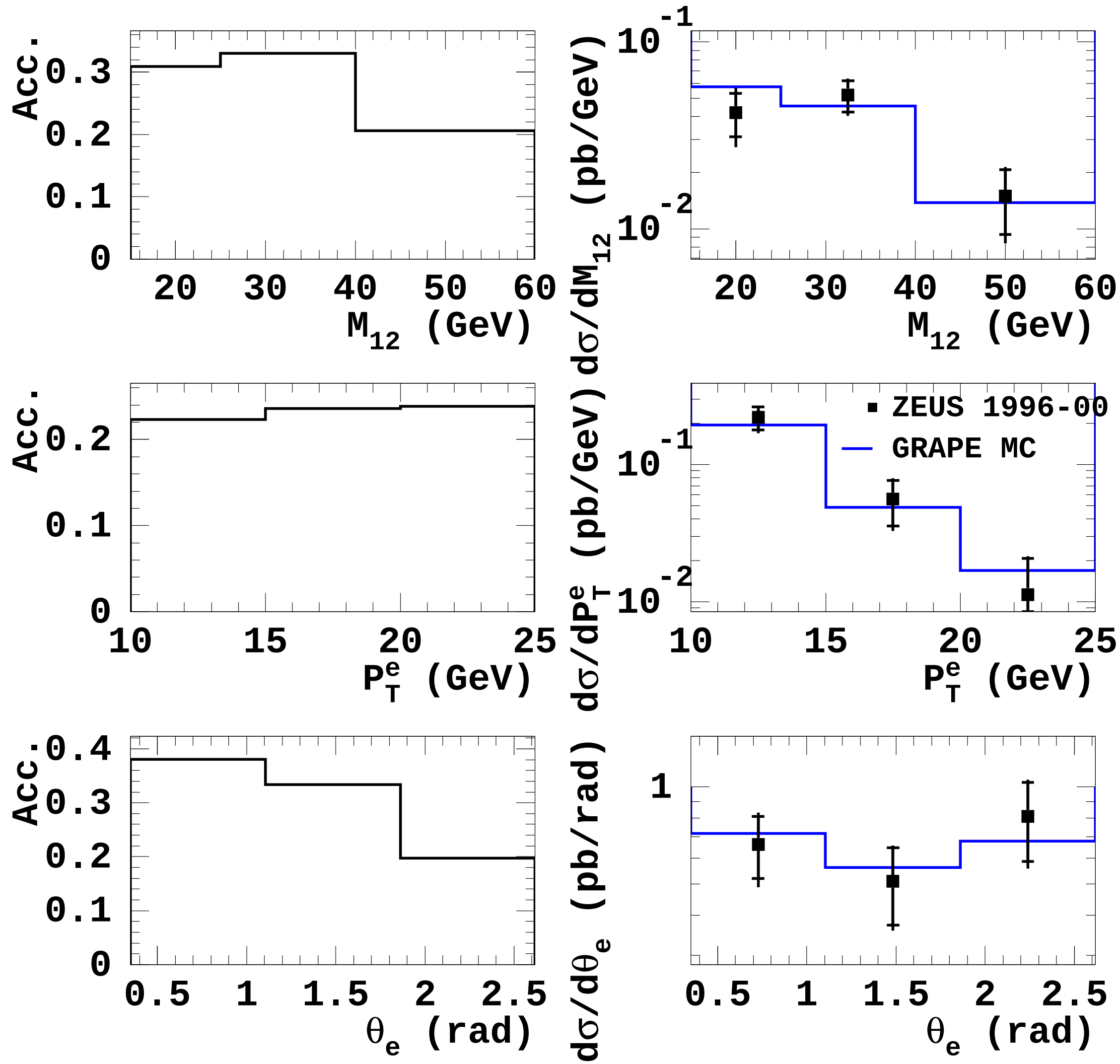
Nice agreement of data and MC.

Total cross section

Period	Purity	Acceptance	$\sigma_{\rm DATA}$ (pb)	$\sigma_{\rm MC}$
1996-97	0.825	0.234	$1.66 \pm 0.43^{+0.18}_{-0.14}$	1.55
1998-99	0.773	0.292	$0.82 \pm 0.41^{+0.13}_{-0.12}$	1.66
1999-00	0.790	0.283	$1.73 \pm 0.31^{+0.22}_{-0.17}$	1.66
1996-00			$1.62 \pm 0.23^{+0.21}_{-0.16}$	

- 1996-97: cross-section is measured at $\sqrt{s} = 300$ GeV.
- 1996-00: cross-section is referred to $\sqrt{s} = 318$ GeV.
- First uncertainty is statistical, second is systematic.
- Main systematics: CAL energy scale simulation ($^{+9.4}_{-4.1}\%$), isolation cut ($+7.3\%$).

Differential cross section



Discussion

- Multi-electron events sought in ZEUS 1996-2000 data.
- Data distributions compared to SM: good description.
- The excess found by H1 is not confirmed.
- Total and differential cross sections were measured: agreement with SM in shape and normalisation.
- Outlook: reduce systematic uncertainties, analyse 1994-95.

Phase space

- 2 electrons in $17^\circ < \theta < 164^\circ$
- $E_T^{e1} > 10$ GeV and $E_T^{e2} > 5$ GeV
- $M_{12} > 5$ GeV
- $E - P_z < 45$ GeV

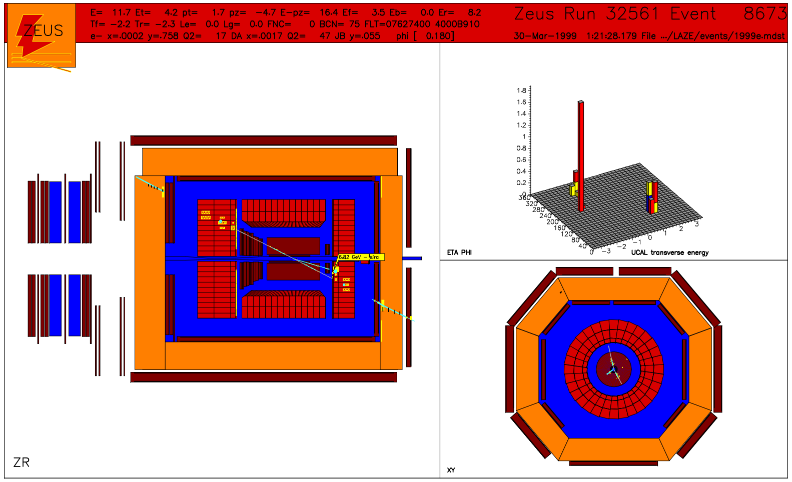
Total cross section

$$\sigma(ep \rightarrow eeeX) = 1.62 \pm 0.23^{+0.21}_{-0.16} \text{ pb}$$

$$\sigma_{\text{MC}} = 1.66 \text{ pb}$$

Di-muon search

Event Selection



Preselection

Fast selection and reduction of data. Selection criteria:

- Trigger selection: B/RMUON activity OR FMUON activity;
- No. of CTD tracks: $2 \leq N_{\mathrm{TrkVtx}} \leq 7$;
- Transverse momentum in CTD: $\sum_i P_{T,i} > 1.5$ GeV.

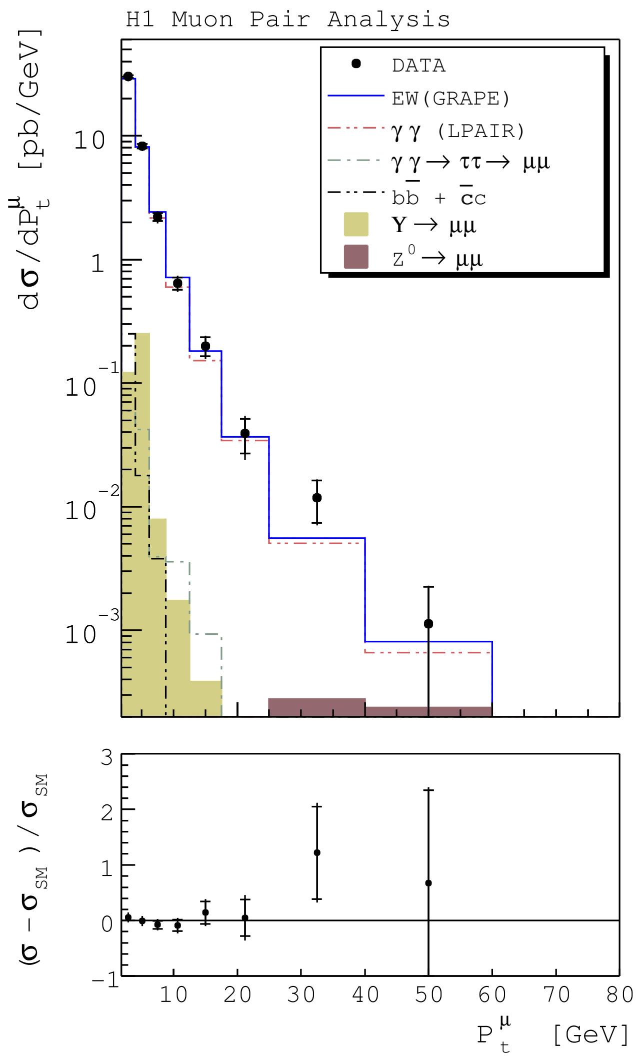
Muon selection

- Muon finding:
  - GLOMU: CTD + CAL + B/RMUI,
  - MPMATCH2: CTD + FMUON,
  - CTD + CAL (MIPs);
- Isolation cut: $D^{\mu}_{\mathrm{Trk}} > 1$ in $\eta\phi$;
- $P_T > 5$ GeV.

Event Selection

- Vertex: $|z| < 50$ cm AND $\sqrt{x^2 + y^2} < 0.5$ cm;
- 2 muons (1 matched to chambers);
- cosmic muons rejection:
  - acollinearity: $\cos\Omega > -0.995$,
  - timing cut.

Backgrounds



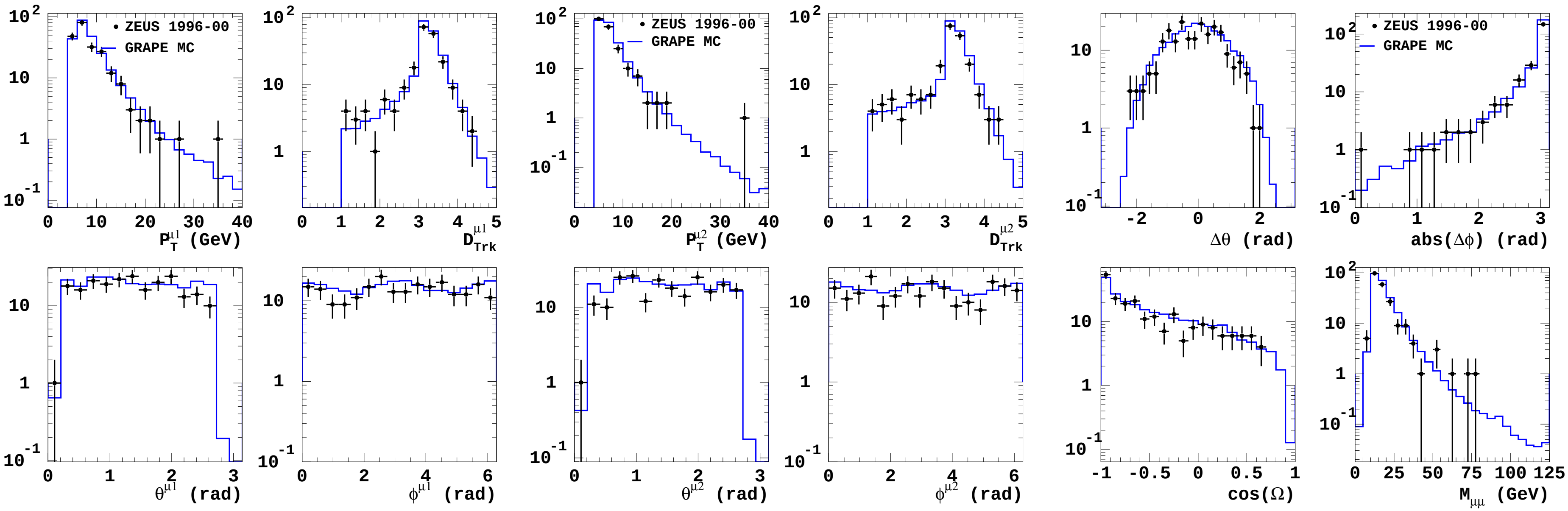
➔ Backgrounds (Υ, heavy quarks and τ decays) were analysed by H1: found to be negligible.

➔ In my analysis they were neglected.

Comparison of data to MC

1996-2000 data taking → L=101.47pb^{-1}

Selection	Data	di-mu MC
All	218	241.14
$M_{\mu\mu} > 50$ GeV	6	3.91
$M_{\mu\mu} > 100$ GeV	0	0.23



→ Three di-muons crowd at $M_{\mu\mu} \simeq 50$ GeV: genuine events.

Monte Carlo describes data reasonably well.

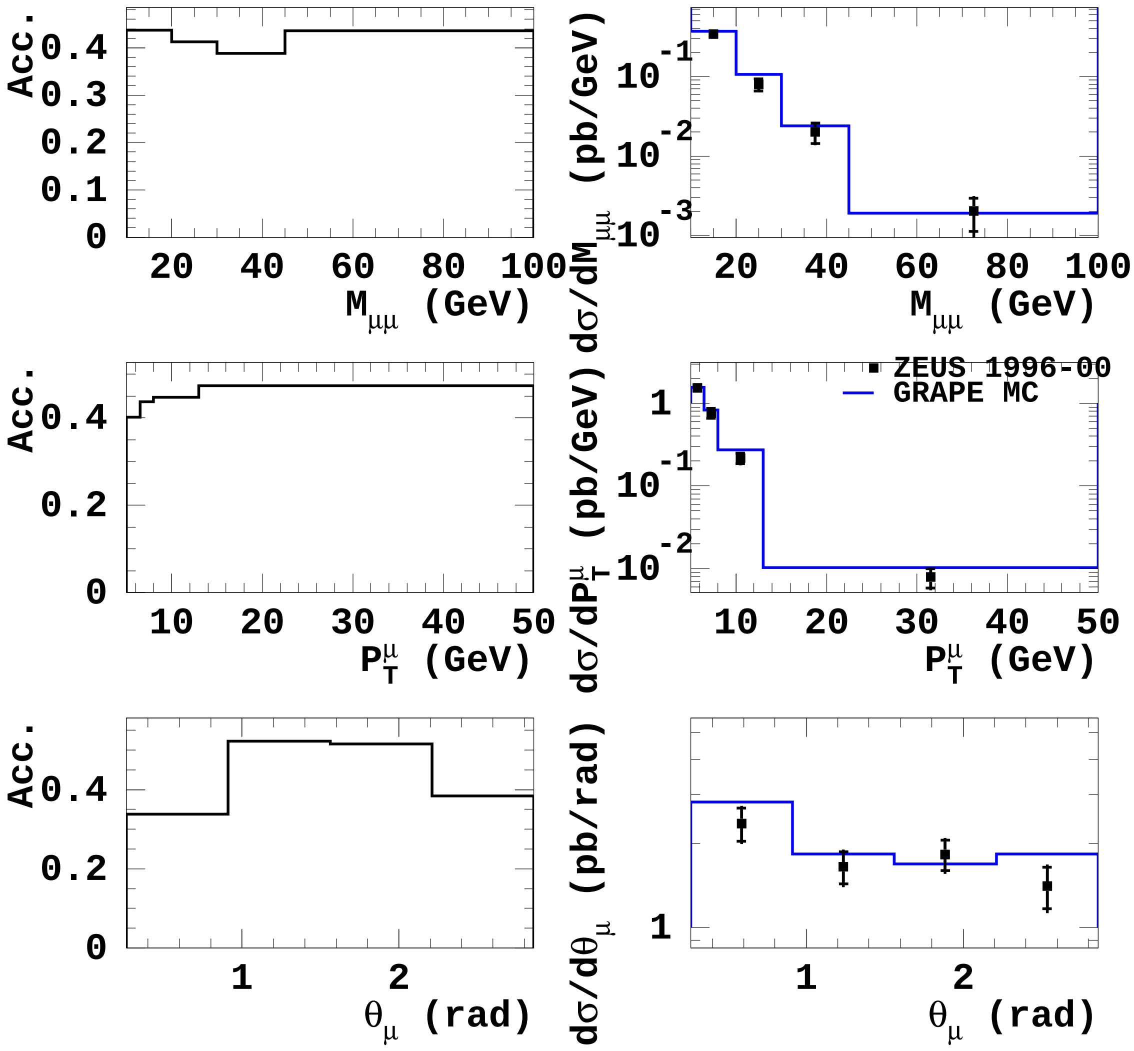
Total cross section

Period	Purity	Acceptance	σ_{DATA} (pb)	σ_{MC}
1996-97	0.953	0.436	$4.65 \pm 0.56^{+0.35}_{-0.31}$	5.31
1998-99	0.956	0.438	$4.97 \pm 0.98^{+0.29}_{-0.27}$	5.21
1999-00	0.968	0.427	$4.81 \pm 0.45^{+0.35}_{-0.33}$	5.32
1996-00			$4.79 \pm 0.33^{+0.35}_{-0.32}$	

- 1996-97: cross-section is measured at $\sqrt{s} = 300$ GeV.
- 1996-00: cross-section is referred to $\sqrt{s} = 318$ GeV.
- First uncertainty is statistical, second is systematic.

- Main systematics: muon chamber eff. ($^{+5.4}_{-4.8}\%$), isolation cut ($+4.0\%$).

Differential cross section



Discussion

- Di-muon events sought in ZEUS 1996-2000 data.
- Data distributions compared to SM: good description.
- 3 events found at $M_{\mu\mu} \sim 50\ \mathrm{GeV}$: genuine di-muons.
- Total and differential cross section were measured: agreement with SM in shape and normalisation.
- Outlook: reduce systematic uncertainties, analyse background ($b\bar{b}$, $c\bar{c}$, Υ, τ decays).

Phase space

- 2 muons in $15^\circ < \theta < 164^\circ$
- $P_T^\mu > 5\ \mathrm{GeV}$
- $M_{\mu\mu} > 5\ \mathrm{GeV}$

Total cross section

$$\sigma(ep \to e\mu\mu X) = 4.79 \pm 0.33^{+0.35}_{-0.32}\ \mathrm{pb}$$

$$\sigma_{\mathrm{MC}} = 5.32\ \mathrm{pb}$$

VCMVD: MVD tracking at ZEUS Third Level Trigger

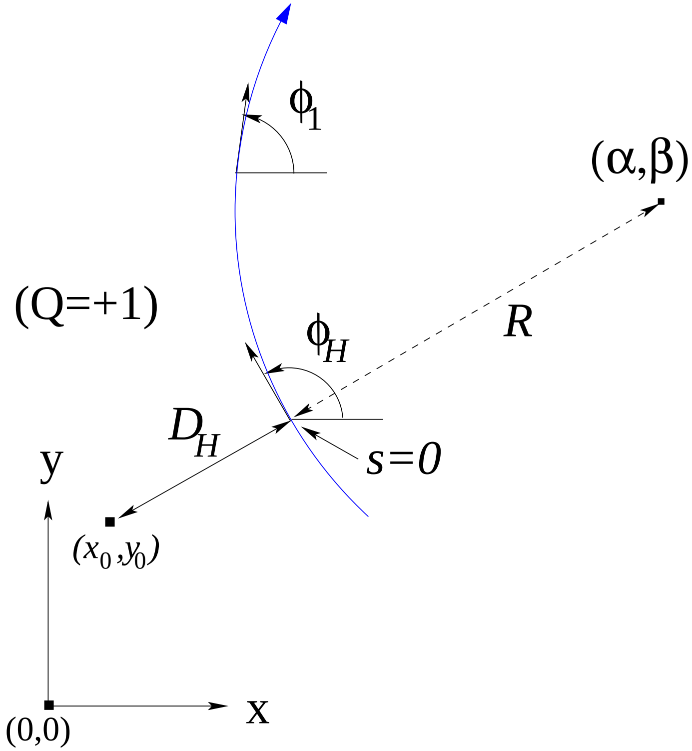
Outline – Part II

- Introduction and motivations
- The ZEUS Micro-Vertex Detector (MVD)
- Description of the method
- Results
- Discussion

Introduction: track parameterisation

➡ Internal detectors are plunged in a magnetic field : charged particles follows helix-like trajectories.

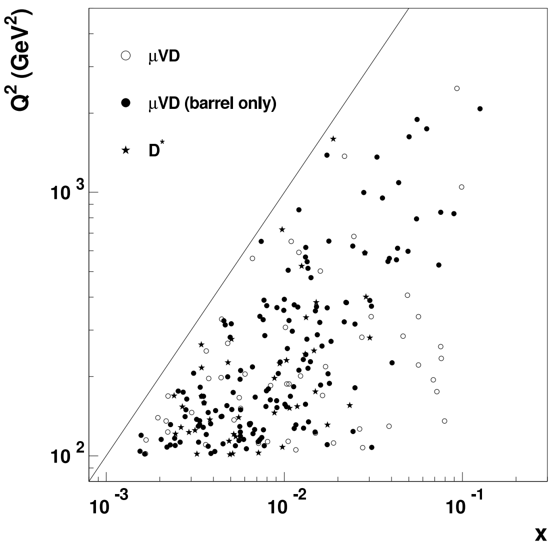
➡ Helices are characterised by 5 parameters a_i and a reference point (x_0, y_0):



- $a_1 = \phi_H$: azimuthal angle at $s = 0$;
- $a_2 = Q/R$: helix curvature;
- $a_3 = Q\ D_H$: closest approach to (x_0, y_0);
- $a_4 = Z_H$: z coordinate at $s = 0$;
- $a_5 = \cot\theta$; θ is the polar angle at $s = 0$.

MVD: motivations

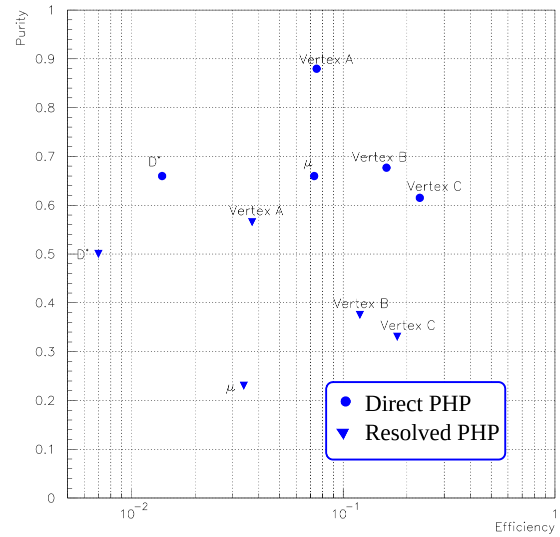
F_2^{charm} measurement



MVD will allow better charm tagging (higher efficiency and larger kinematical range).

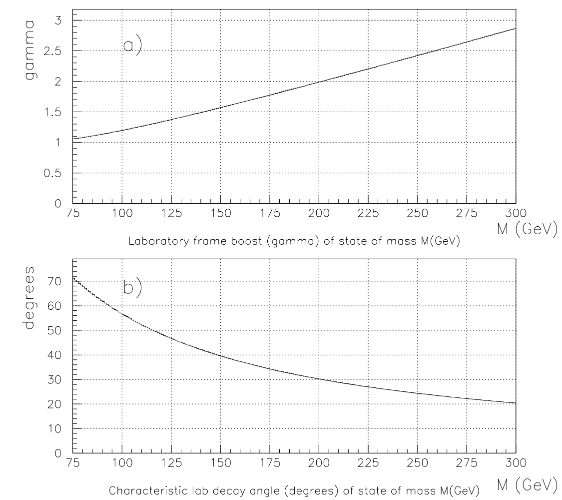
➔ Measurement of F_2^{charm} and gluon density.

Photoproduction of jets



MVD will allow better tagging of resolved and direct charm/beauty photoproduction and thus better event selection and cross-section measurement.

Exotic processes



Heavy states are boosted forward.

➔ daughters' decay lenghts may be detected even if particles are short-lived.

VCMVD: motivations

- After Micro-Vertex Detector (MVD) installation in 2001 the ZEUS tracking package (VCTRAK) needed to be updated to benefit from the new detector
- A “fast” algorithm was needed for the use in the Third Level Trigger (TLT)
- VCMVD (VCtrak+MVD) has been developed to refine VCTRAK tracks by means of MVD hits
- Effects: great improvement in a_4, a_3 precision.

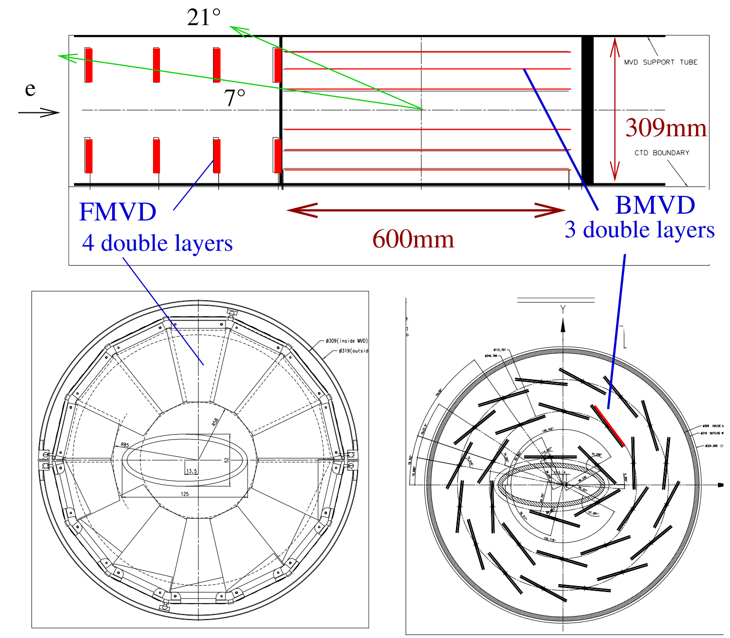
The ZEUS MVD

Barrel Section

- 3 layers of silicon detectors;

➡ each layer measures 2 views: $r\phi$ and z;

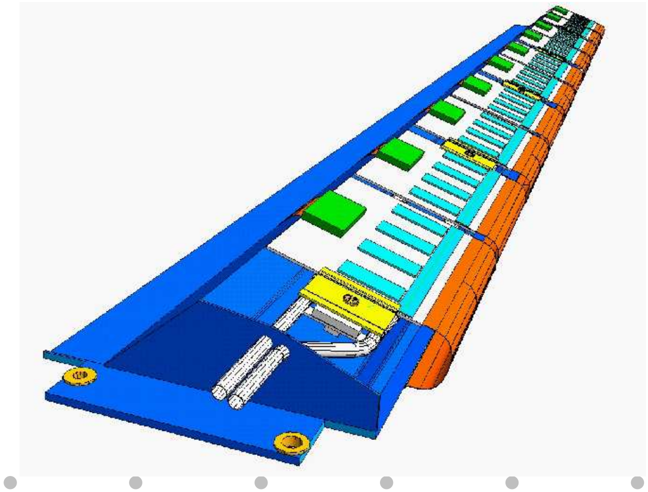
- intrinsic resolution: $\sim$ 20 μm;
- angular coverage (3 layers): $22^\circ < \theta < 159^\circ$.



112 detectors (trapez.)   600 detectors (square)

Forward wheels

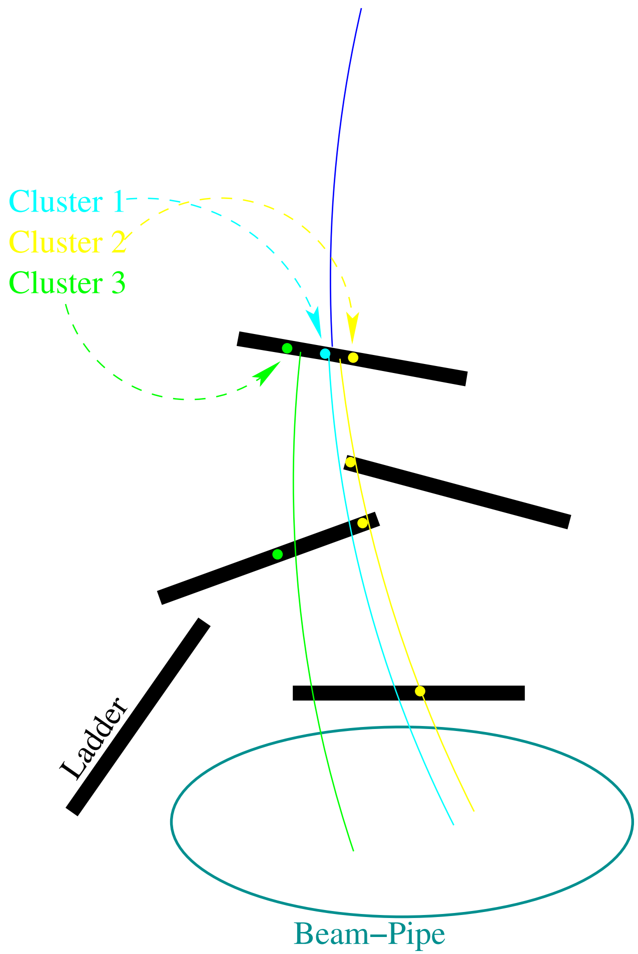
- 4 wheels of silicon detectors;
- extend coverage to $\theta = 7^\circ$.



➡ Only BMVD is used in the package.

VCMVD: the method

- Tracks are found in CTD by VCTRAK;
- MVD hits are reconstructed;
- VCTRAK tracks are propagated from CTD to MVD;
- MVD hits are collected on the outer layer;
- track parameters are updated;
- the same procedure is repeated for middle and internal layers.



Results: efficiency

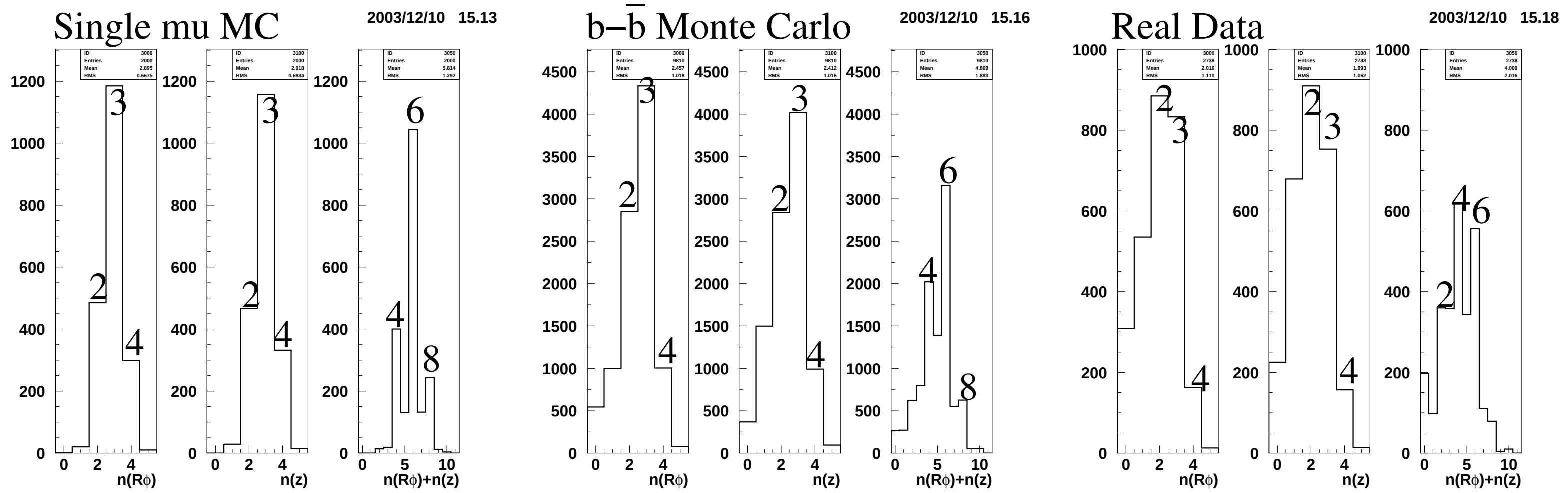
Geometrical coverage

- 2 layers: 72° in ϕ;
- 3 layers: 288° in ϕ;

→ Expected intersections: $\langle n \rangle \simeq 2.8$/track/view.

Assigned clusters

- Single muon MC: $\langle n \rangle = 2.9$;
- $b\bar{b}$ MC: $\langle n \rangle = 2.4 \div 2.5$;
- Data (offline): $\langle n \rangle = 2.0$.

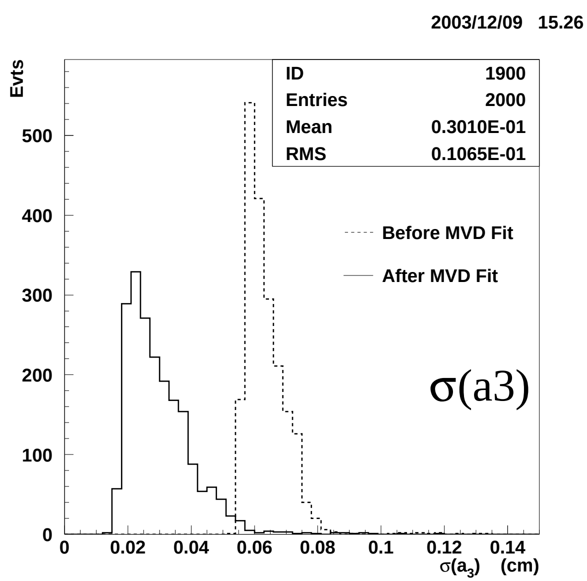


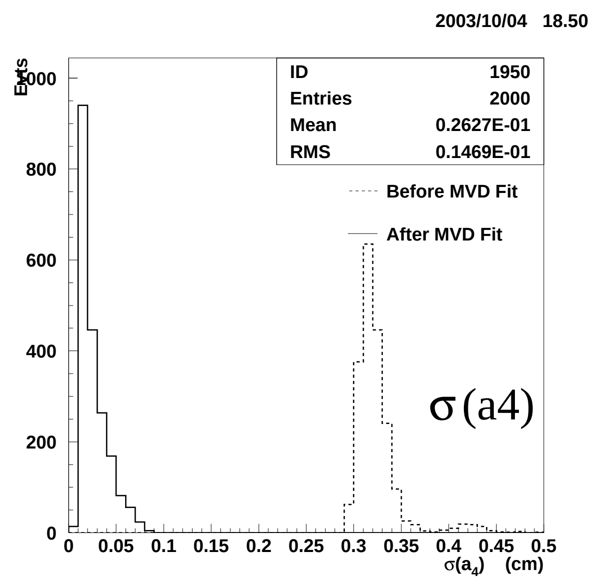
Results: D_H and Z_H

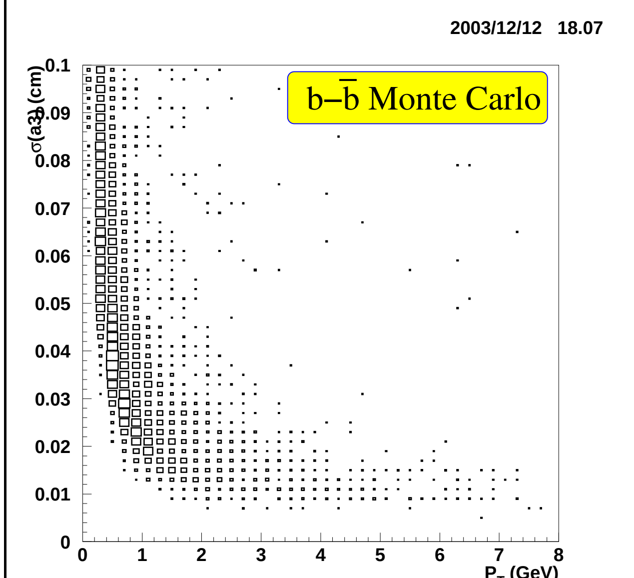
SAMPLE: Single muon Monte Carlo, $p_T = 0.5 \div 1.5$ GeV

Results

- $\sigma(D_H)$: 650 μm (VCTRAK) $\rightarrow$ 300 μm (VCMVD);
- $\sigma(Z_H)$: 3.2 mm (VCTRAK) $\rightarrow$ 0.26 mm (VCMVD).





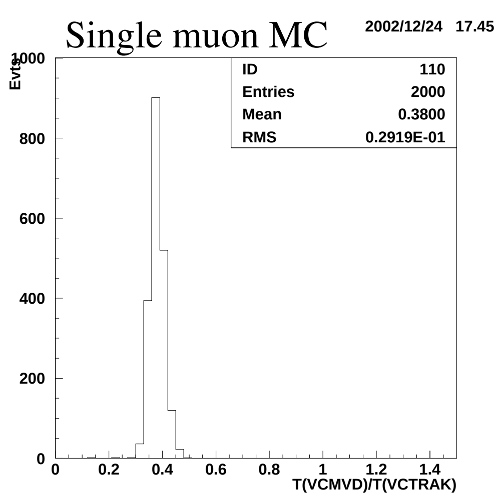


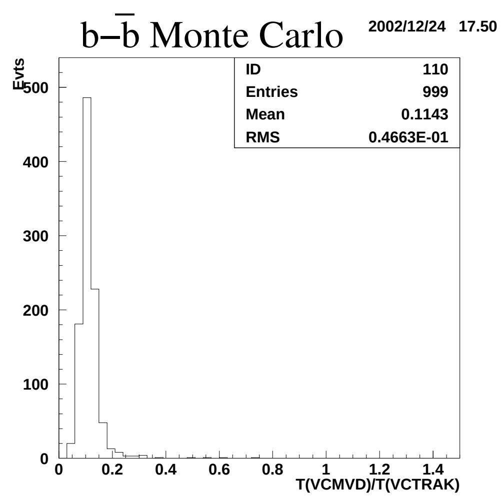
- $\sigma(D_H) \rightarrow 100$ μm at high-P_T

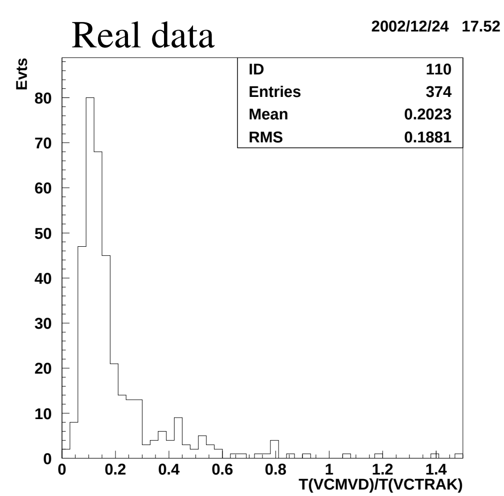
Results: Execution Time

➜ The execution time is evaluated as fraction of VCTRAK (CTD tracking package) time.

- Monte Carlo: 40% (single muon) $\longrightarrow$ 11% ($b\bar{b}$).
- Data (offline): 20 $\div$ 25%.





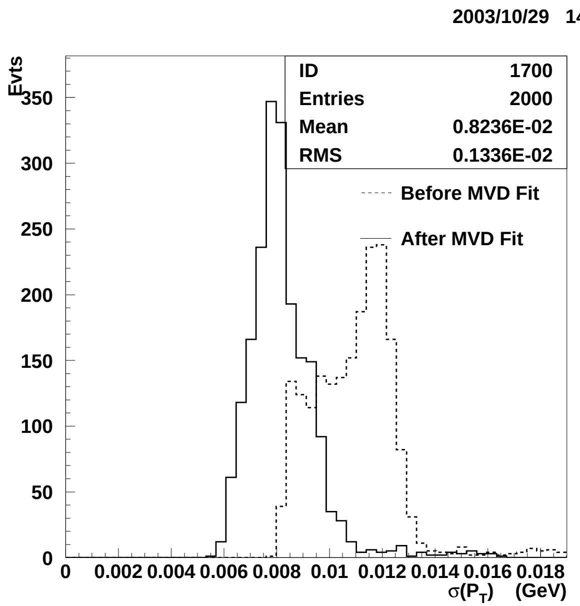


➜ Absolute execution time increases steeply for VCTRAK

Results: P_T and probabilities

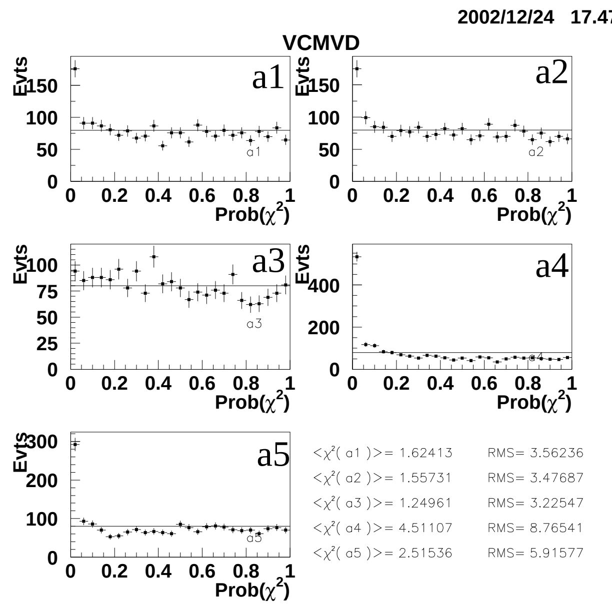
SAMPLE: Single muon Monte Carlo, $p_T = 0.5 \div 1.5$ GeV

P_T measurement



- $\sigma(P_T, \text{VCTRAK}) = 11$ MeV.
- $\sigma(P_T, \text{VCMVD}) = 8$ MeV.

Probability of a_i:



Definition of probability:

$$P\left(\frac{(a_\nu^{\text{fit}} - a_\nu^{\text{true}})^2}{\sigma_{\text{fit}}^2}, 1\right)$$

➜ Flat probabilities: fitting procedure is correct.

➜ Peaks at 0: hint of non gaussian tails.

Discussion

- A new vertex detector has been installed in 2001 at ZEUS
- The VCMVD tracking package has been developed to update VCTRAK parameters
- VCMVD package has been tested offline: very good results in execution time and tracking improvement
- VCMVD has been implemented in the online software: data are coming for further testing

Conclusions

Conclusions

Part I

- HERA collisions have been analysed in the search for multi-electron and di-muon events
- The data are nicely described by the SM simulation
- The excess observed by H1 in high-mass di/trielectrons is not confirmed

Part II

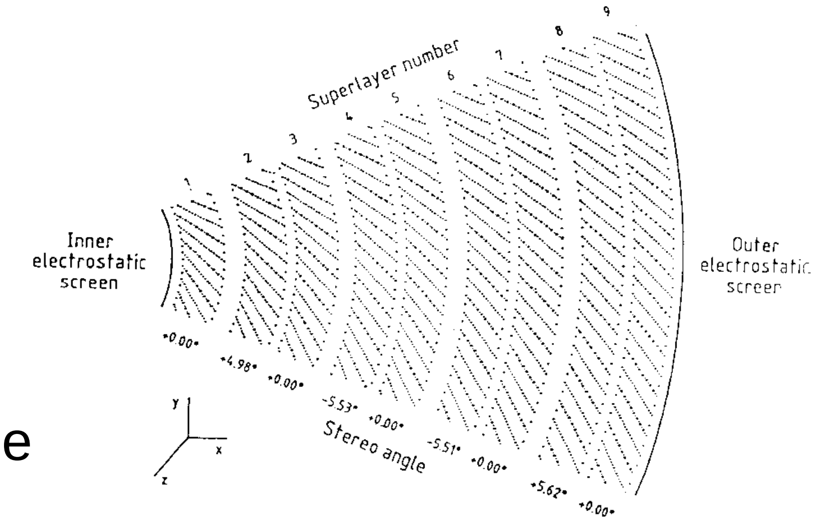
- A tracking package, VCMVD, has been developed for use of MVD in TLT
- VCMVD behaves well on (offline) data and MC
- Online data are coming for testing

ADDITIONAL SLIDES

The ZEUS detector

The Central Tracking Detector (CTD)

- Cylindrical wire drift chamber, 72 layers of sense wires divided into 9 super-layers.
- -100 cm $< z <$ 104 cm, $15^\circ < \theta < 164^\circ$.
- Filled with Ar, CO_2 and C_2H_6 (ethane) in the proportion 85:5:1.
- Wires are tilted by 45° to compensate the Lorentz angle.



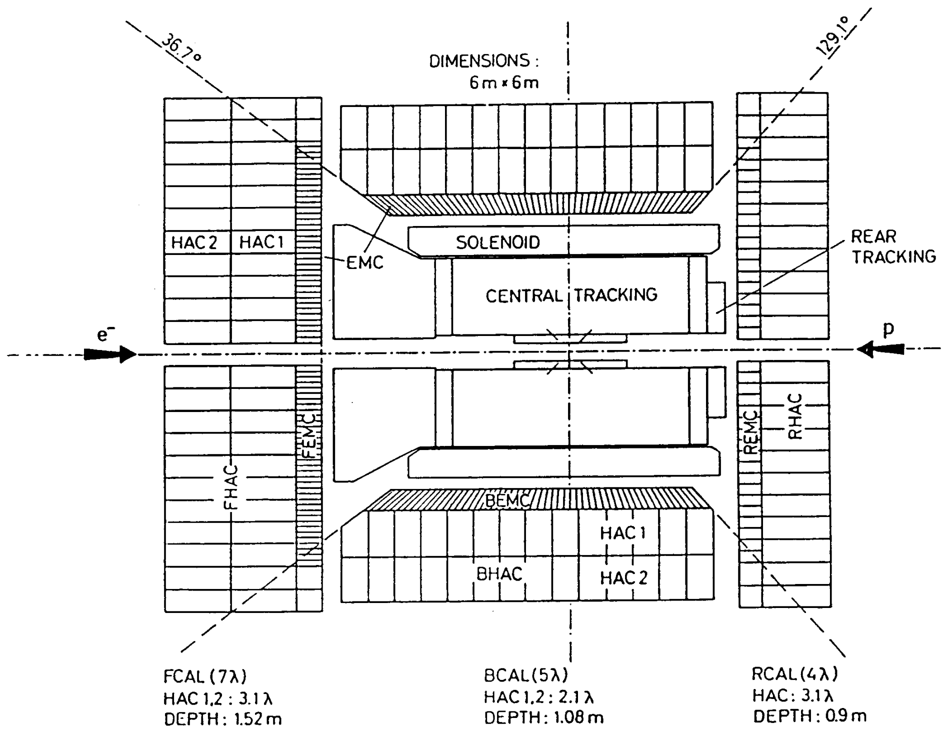
The resolution on p_T for tracks with $p_T > 150$ MeV, constrained to the interaction vertex and passing three CTD super-layers is

$$\frac{\sigma(p_T)}{p_T} = 0.0058 \cdot (p_T/\mathrm{GeV}) \oplus 0.0065 \oplus \frac{0.0014}{(p_T/\mathrm{GeV})}.$$

The CTD also supplies information on the energy loss $\mathrm{d}E/\mathrm{d}x$.

The Uranium Calorimeter (CAL)

- Longitudinally divided into three parts (RCAL/BCAL/FCAL).
- Surrounds the tracking devices and the solenoid.
- Consists of 3.3 mm thick depleted uranium plates alternated with 2.6 mm thick organic scintillator.
- Compesation: same response for electrons and hadrons.



Electromagnetic energy resolution

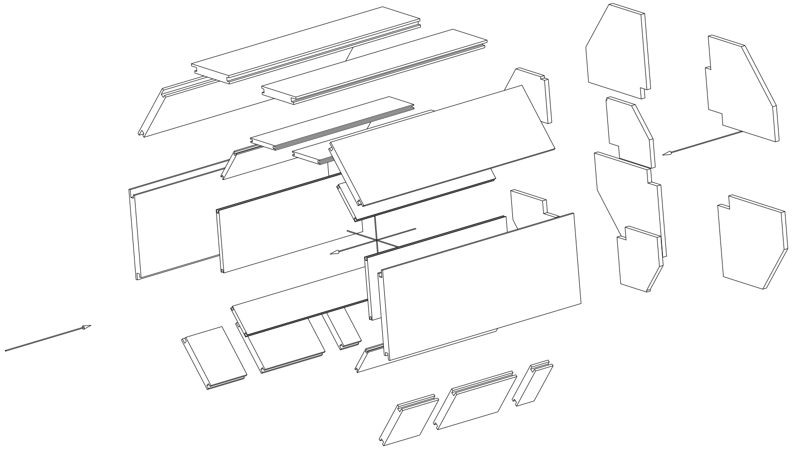
$$\frac{\sigma(E)}{E} = \frac{18\%}{\sqrt{E/\mathrm{GeV}}} \oplus 2\%$$

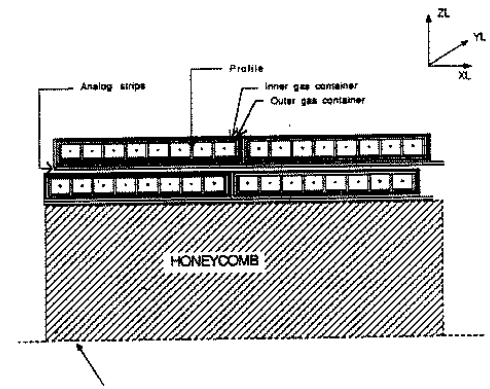
Hadronic energy resolution

$$\frac{\sigma(E)}{E} = \frac{35\%}{\sqrt{E/\mathrm{GeV}}} \oplus 1\%$$

The Barrel/Rear Muon Chambers

- Large area to be covered $\Rightarrow$ modular structure based on the chamber.
- Two layers of LST tubes placed on both sides of a honeycomb support structure.
- x and y coordinates read by each LST plane (signal induced on conductive strips orthogonal to the wires, glued outside the plane).
- Cells filled with Ar, CO_2 and C_4H_{10} (isobutane).
- Chambers have different shape and dimension, depending on their position.





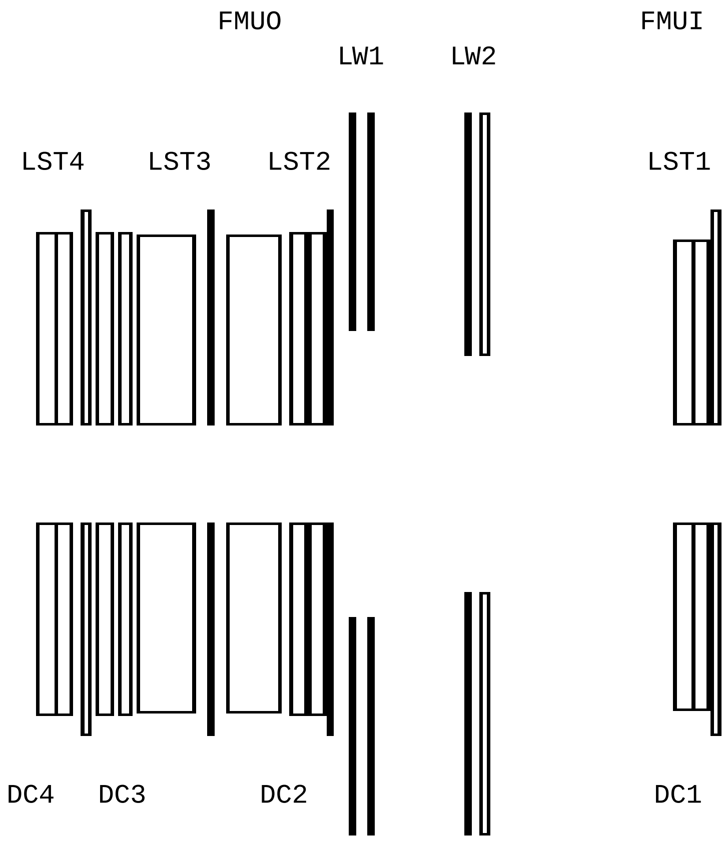
⋆ BMUI-RMUI: chambers between the CAL and the yoke.

⋆ BMUO-RMUO: chambers outside the yoke.

The Forward Muon Chambers

The FMUON detector consists of:

- 4 LST trigger planes, with digital ρ and ϕ read-out (LST1–4);
- Two coverage planes of LSTs, in the large polar angle region (LW1–2);
- 4 planes of drift chambers (DC1–4);
- Two large toroidal magntes, providing a 1.7 T field for momentum separation and measurement in the small polar angle region.



$\star$ FMUI: LST1–DC1, inside the yoke.

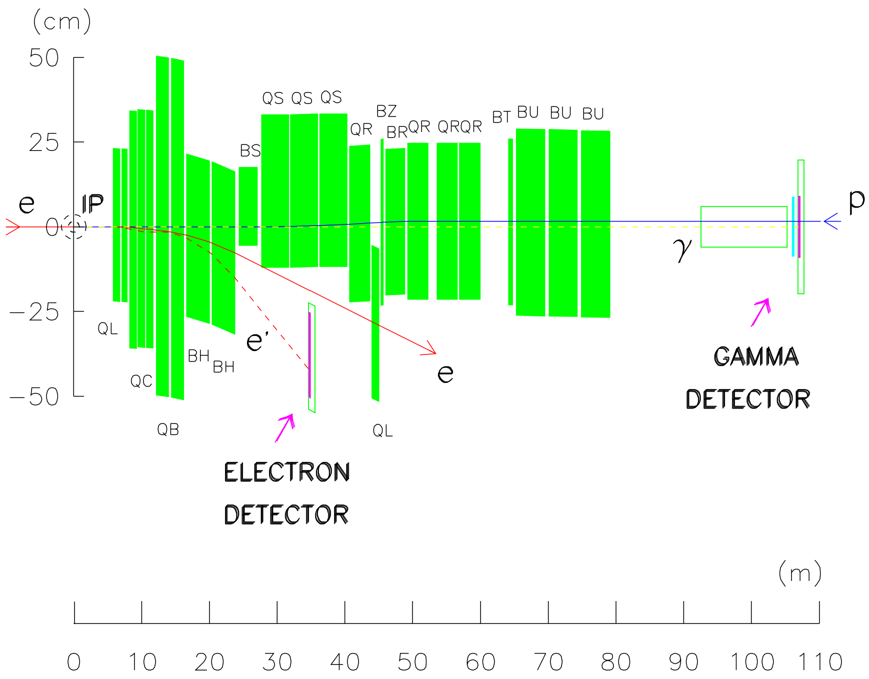
$\star$ FMUO: other chambers, outside the yoke.

The Lumi Monitor

- Photon calorimeter at $z = -(104 \div 107)$ m.
- Resolution:

$$\frac{\sigma(E)}{E} = \frac{23\%}{\sqrt{E/\mathrm{GeV}}}.$$

- Photons from $ep \to ep\gamma$ are counted.
- Luminosity is extracted using Bethe-Heitler formula for $\sigma(ep \to ep\gamma)$.
- Precision: $\sigma(L)/L = 1 \div 2\%$.



Past results

Multi-electrons at H1

Data taking: 1994-00 Lumi used: 115.2 pb^{-1}

Event Selection

- Two "central" ($20^\circ < \theta < 150^\circ$), "isolated", electrons
- P_T cut: $P_T^{e1} > 10$ GeV, $P_T^{e2} > 5$ GeV

Event Classification

- "2e": Only 2 central electrons
- "3e/4e": Additional "isolated" electrons (also Forward and Rear)

"$\gamma\gamma$" subsample

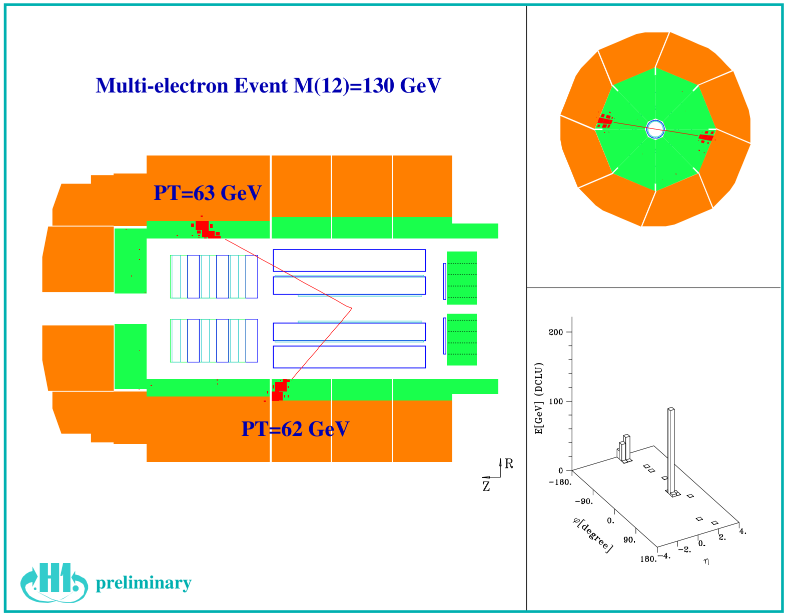
- Just 2 opposite charge electrons: $ep \rightarrow e^+e^-X$
- $E - P_z < 45$ GeV (ie $y < 0.82$, $Q^2 < 1\ \mathrm{GeV}^2$)

➡ "Cleaner" sample; scattered electron is lost in beam–pipe; both detected electrons come from interaction

Multi-electrons at H1

- Different topology for “2e” and “3e” events:

A “2e” event:

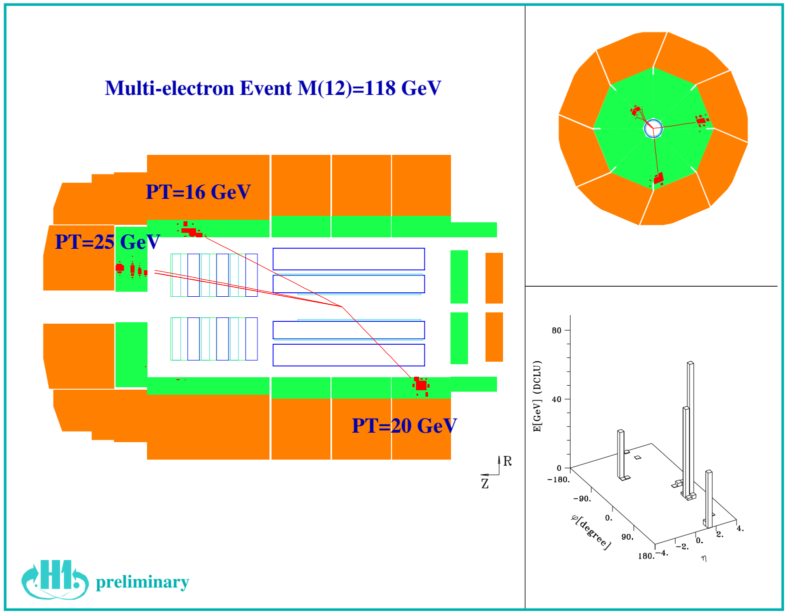


P_T^{e1} = 63 GeV, P_T^{e2} = 62 GeV

M_{12} = 130 GeV

- Harder P_T in “2e”

A “3e” event:

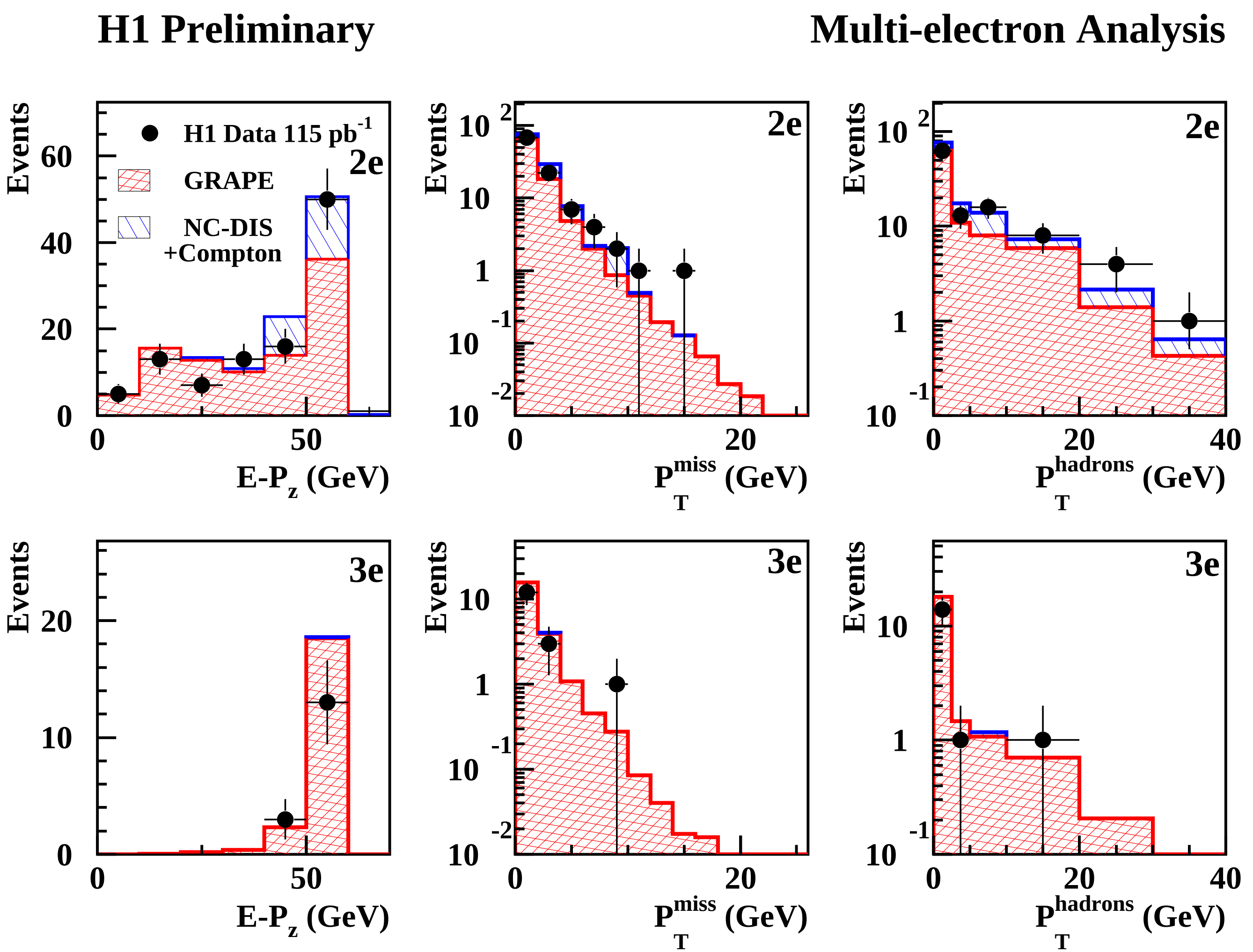


P_T^{e1} = 25 GeV, P_T^{e2} = 20 GeV

M_{12} = 118 GeV

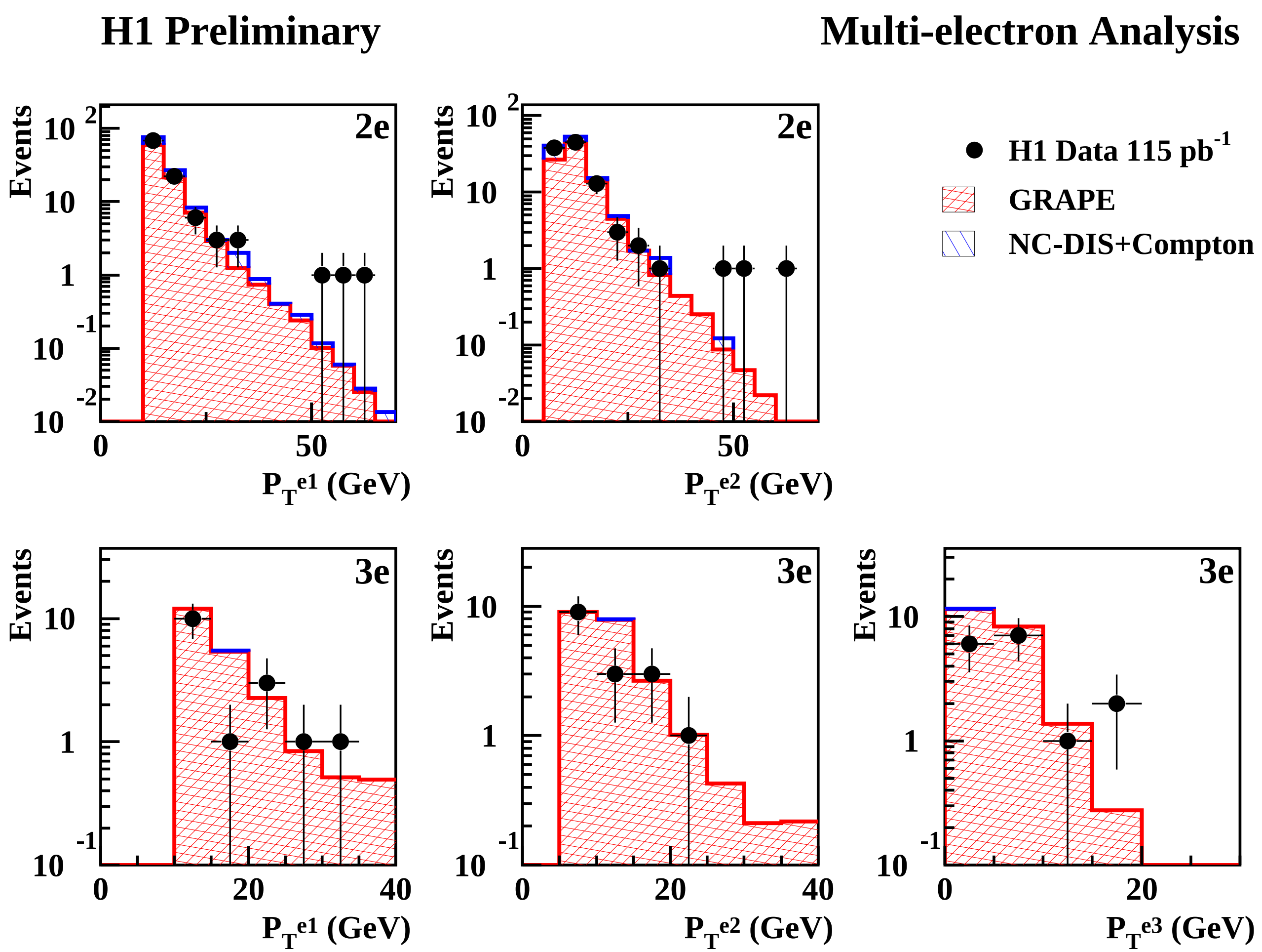
- More forward es in “3e”

Multi-e at H1: global variables



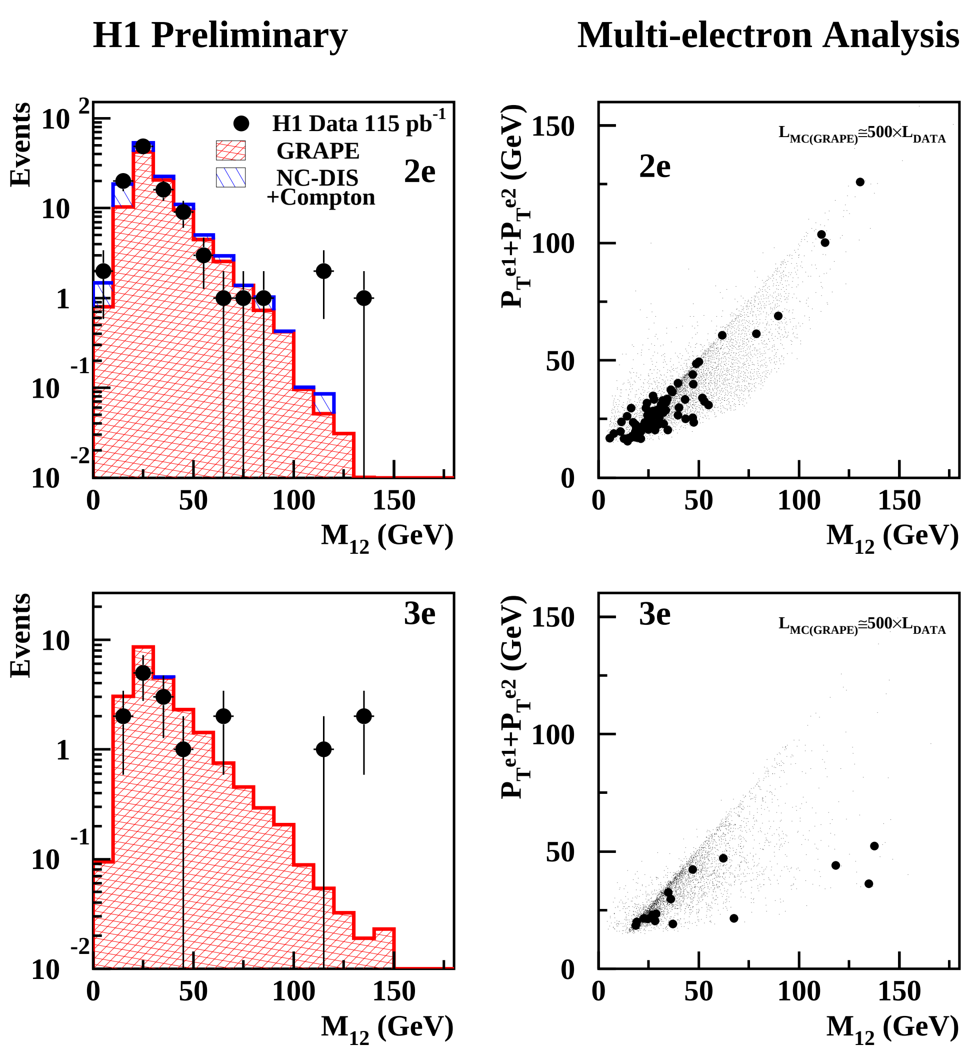
- GRAPE: $\gamma\gamma$ interaction + γ & Z^0 conversion
- NC-DIS + Compton: fake "2e"-"3e" events

Multi-e at H1: electron variables



➔ Three “2e” events with $P_T^{e1} > 50$ GeV (but low SM expectation)

Multi-e at H1: Mass distributions



- M_{12} = Mass of two highest P_T electrons
- Harder P_T for "2e"

At $M_{12} > 100$ GeV

- "2e" events:

3 found

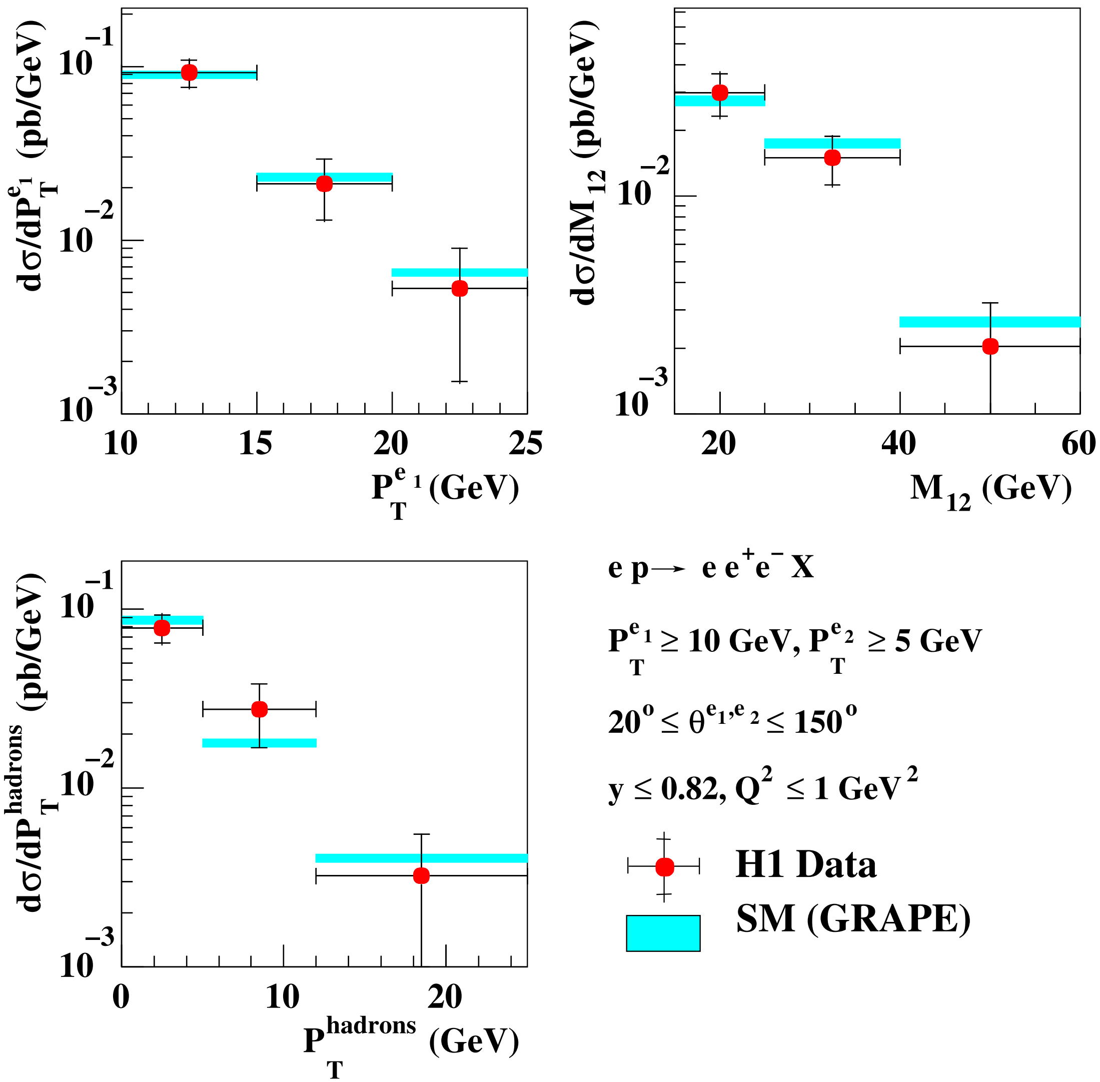
0.25±0.05 expected

- "3e" events:

3 found

0.23±0.04 expected

Multi-e at H1: $\gamma\gamma$ Cross Section



- Extracted from "$\gamma\gamma$" sample
- Good Agreement with SM

Multi-electrons at H1: Overview

Selection	DATA	SM	GRAPE	NC-DIS + Compton
Visible 2e	105	118.2±12.8 *	93.3±11.5	25.0±5.5
Visible 3e	16	21.6±3.0	21.5±3.0	0.1±0.1
Visible 4e or more	0	0.1±0.0	0.1±0.0	0.0±0.0
$\gamma\gamma \rightarrow e^+e^-$ subsample	41	48.3±6.1	46.4±6.1	1.9±0.9
Visible 2e $M(12)$ >100	3	0.25±0.05	0.21±0.04	0.04±0.03
Visible 3e $M(12)$ >100	3	0.23±0.04	0.23±0.04	0.00±0.00

* Statistical $\oplus$ Systematic Uncertainty

- DATA agree with SM at low M_{12}
- Excess in DATA at high M_{12}

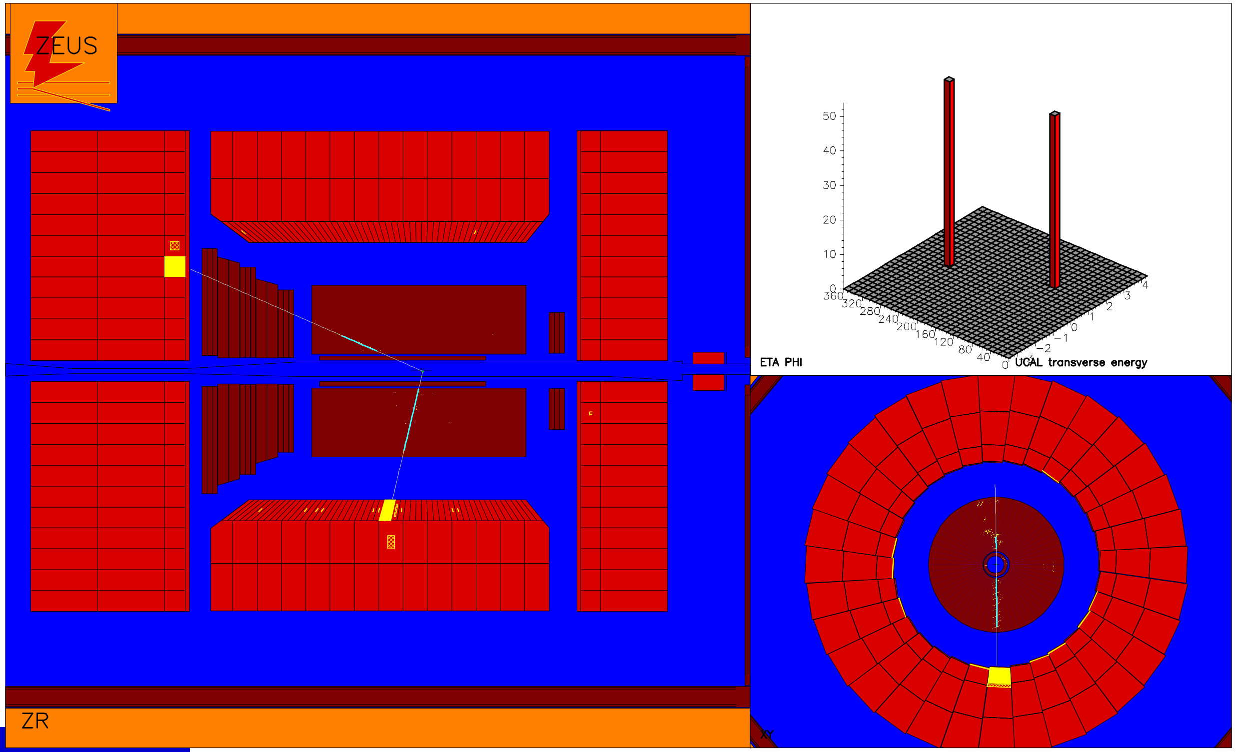
Multi-electrons at ZEUS

Data taking: 1994-00 Lumi used: 130.5 pb^{-1}

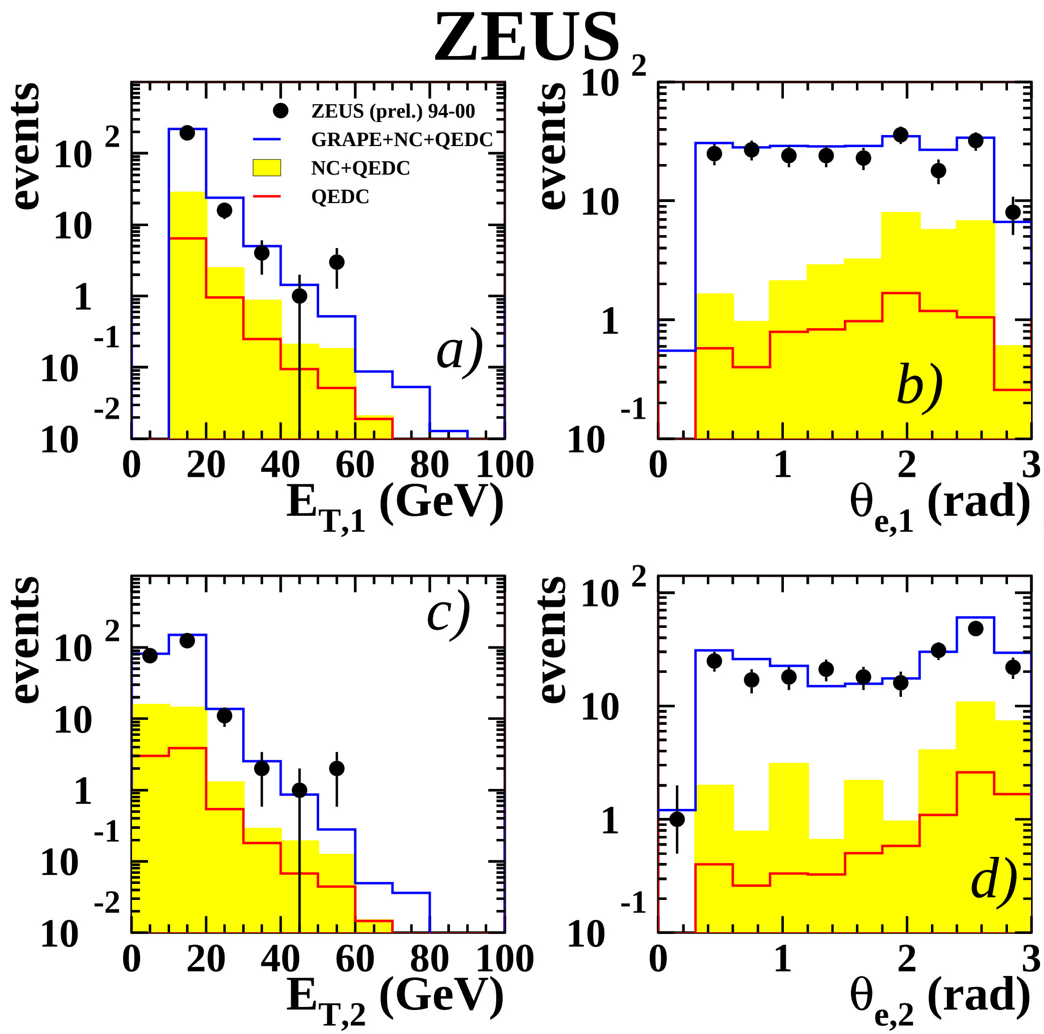
Event Selection

- "Good Vertex": $|Z_{\text{vtx}}| < 50$ cm
- Two "central" ($17° < \theta < 164°$) electrons: $E_T^{e1} > 10$ GeV, $E^{e2} > 10$ GeV

A "2e" event →

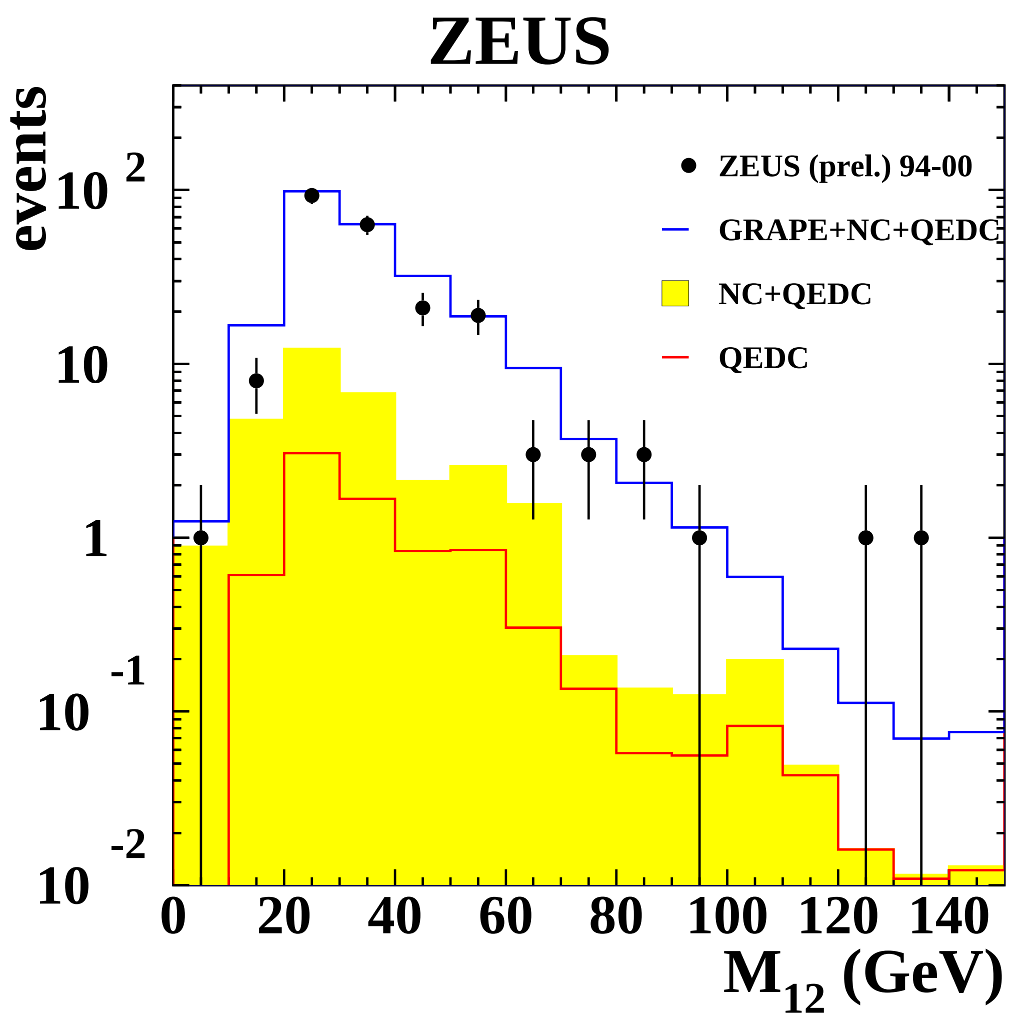


Multi-e at ZEUS: electron variables



→ Good Agreement

Multi-e at ZEUS: Mass distribution



➔ Two events with $M_{12} > 100$ GeV; expected 1.2±0.1

Multi-e at ZEUS: Overview

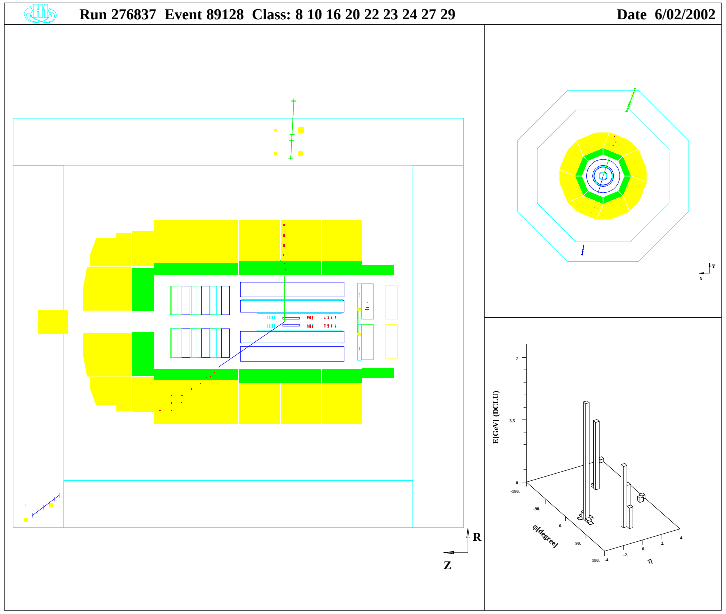
Type	Data	SM	GRAPE	NC-DIS	Compton
2e sample					
2e	191	213.9±3.9 *	182.2±1.2	23.9±3.7	7.8±0.5
$E_T^{e1} > 30$ GeV	6	5.7±0.3	4.4±0.2	0.9±0.2	0.4±0.1
$M_{12} > 100$ GeV	2	0.77±0.08	0.47±0.05	0.12±0.06	0.18±0.03
3e sample					
3e	26	34.7±0.5	34.7±0.5	-	-
$E_T^{e1} > 30$ GeV	2	1.43±0.08	1.43±0.08	-	-
$M_{12} > 100$ GeV	0	0.37±0.04	0.37±0.04	-	-

* Only Statistical Error

Di-Muons at H1

Data taking: 1999-00

Lumi used: 70.9 pb^{-1}



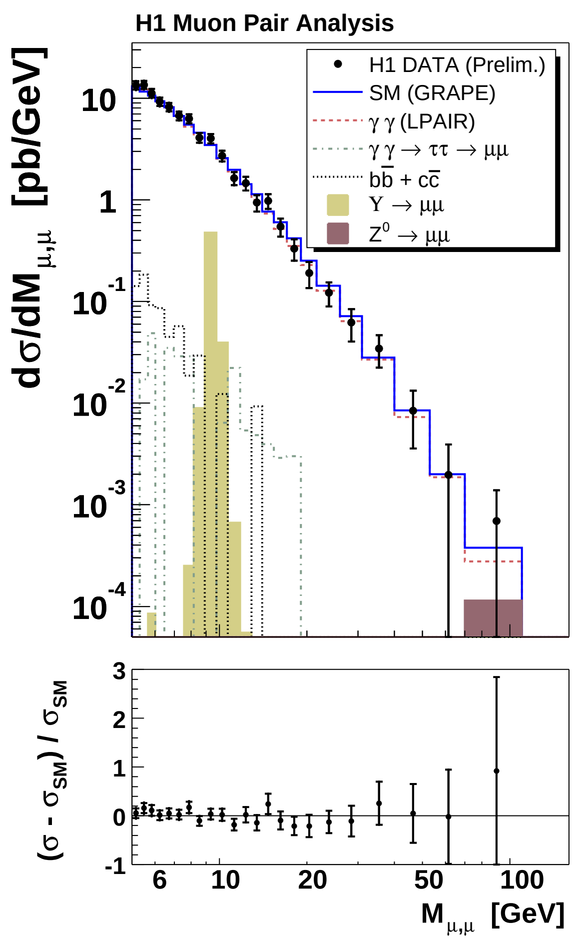
Muon Selection

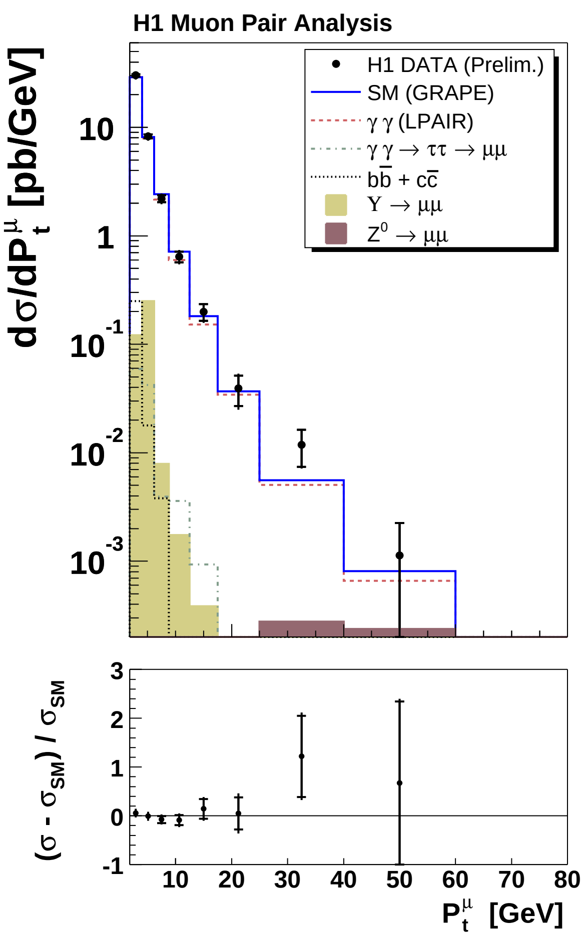
- Reconstructed track in both CTD and Muon Detectors
- Angular region: $20^\circ < \theta < 160^\circ$
- For low momentum muons: CTD Track + Calorimeter MIP

Event Selection

- Two muons: $P_T^{\mu 1} > 2.00$ GeV, $P_T^{\mu 2} > 1.75$ GeV
- Invariant mass cut: $M_{\mu\mu} >$ 5 GeV
- Muon Isolation: $D^{\mu}_{\mathrm{Trk,jet}} >$ 1.0 in $\eta\phi$ (or $D^{\mu}_{\mathrm{Trk,jet}} >$ 0.5 if $P_T^{\mu} > 10$ GeV)

Di-Muons at H1: Cross section



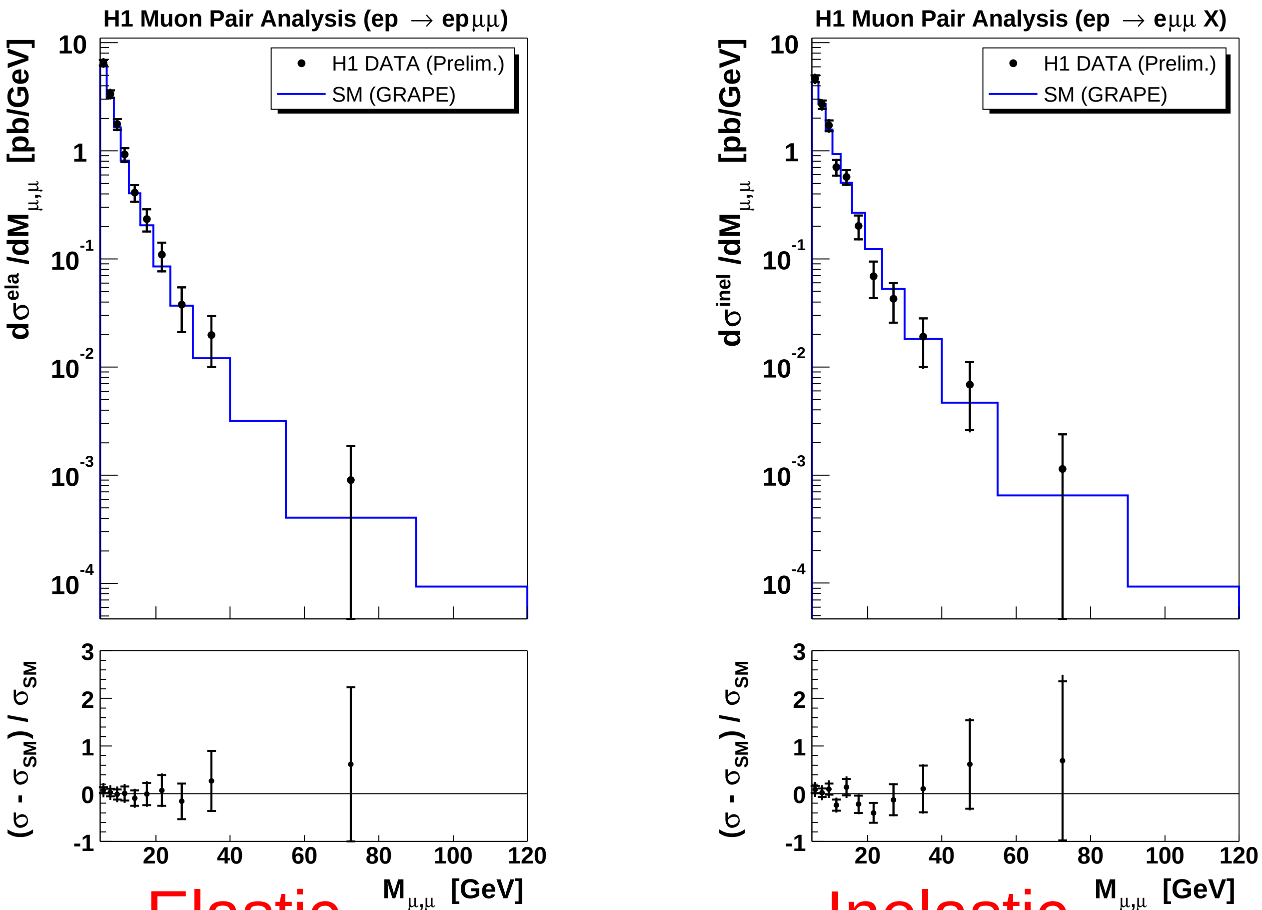


- Main contribution: $\gamma\gamma$ interaction
- Small contribution to $\mu^+\mu^-$ from: Υ, $q\bar{q}$ and $\tau\tau$ decays

➔ Total Cross–Section: $\sigma = 46.5 \pm 1.3 \pm 4.7$ pb

➔ Good Agreement with SM: $\sigma(\mathrm{GRAPE}) = 46.2$ pb

Di-Muons at H1: Cross section



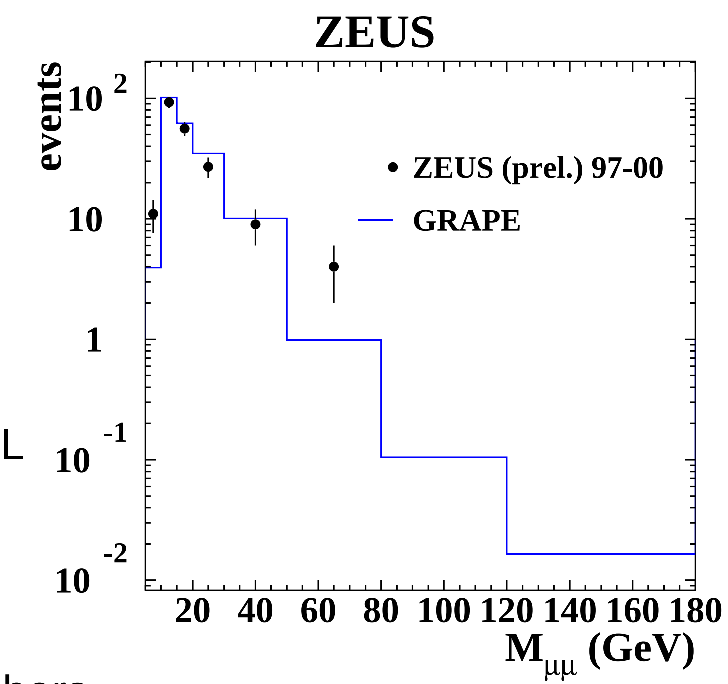
Elastic Inelastic

- Elastic and Inelastic separated by tagging proton remnant

➔ Inelastic Cross–Section: $\sigma^{\rm inel} = 20.8 \pm 0.9 \pm 3.3$ pb

➔ Good Agreement with SM: $\sigma^{\rm inel}(\mathrm{GRAPE}) = 21.5$ pb

Di-Muons at ZEUS



Data taking: 1997-00

Lumi used: 105.2 pb^{-1}

Muon Selection

- Track in CTD ($P_T >$ 5 GeV)+ MIP in CAL
- Angular region: $20^\circ < \theta < 160^\circ$

Event Selection

- Two muons: 1μ matched to muon chambers
- Muon Isolation: $N_{\rm trks}(R_{\eta\phi} < 1)$ = 0
- Good Vertex: $|Z_{\rm vtx}| <$ 40 cm, $\sqrt{X^2_{\rm vtx} + Y^2_{\rm vtx}} <$ 0.5 cm
- Acollinearity: $\cos(\Omega) > -$0.995

Multi-electron search

The electron tagging

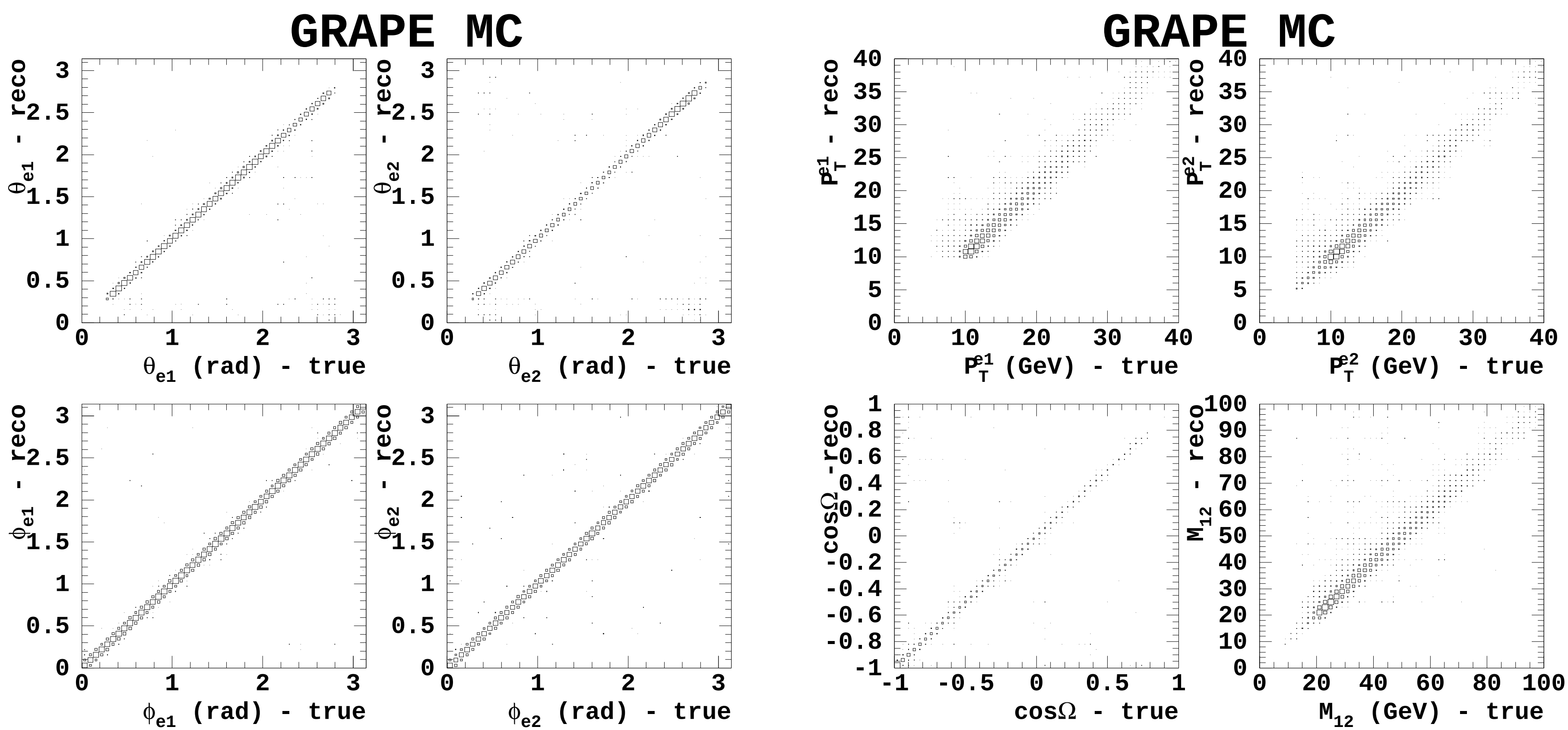
The EM electron finder analyses energy deposits in the CAL to distinguish electromagnetic from hadronic clusters.

Sketch of the algorithm:

- Calorimeter cells are grouped in clusters;
- 4 quantities are evaluated for each cluster:
  - fraction of hadronic energy,
  - fraction of electromagnetic energy outside two highest-energy modules,
  - fraction of energy outside two highest-energy modules,
  - non-electron energy in a R=0.8 cone in $\eta\phi$;
- when a CTD track matches the cluster, are evaluated:
  - $\theta_{\rm Trk} - \theta_{\rm Cal}$,
  - $\phi_{\rm Trk} - \phi_{\rm Cal}$,
  - $1/P_{\rm Trk} - 1/E_{\rm Cal}$;
- a probability is computed using the above defined quantities.

Variable reconstruction

Very nice correlation of true and reconstructed variables:



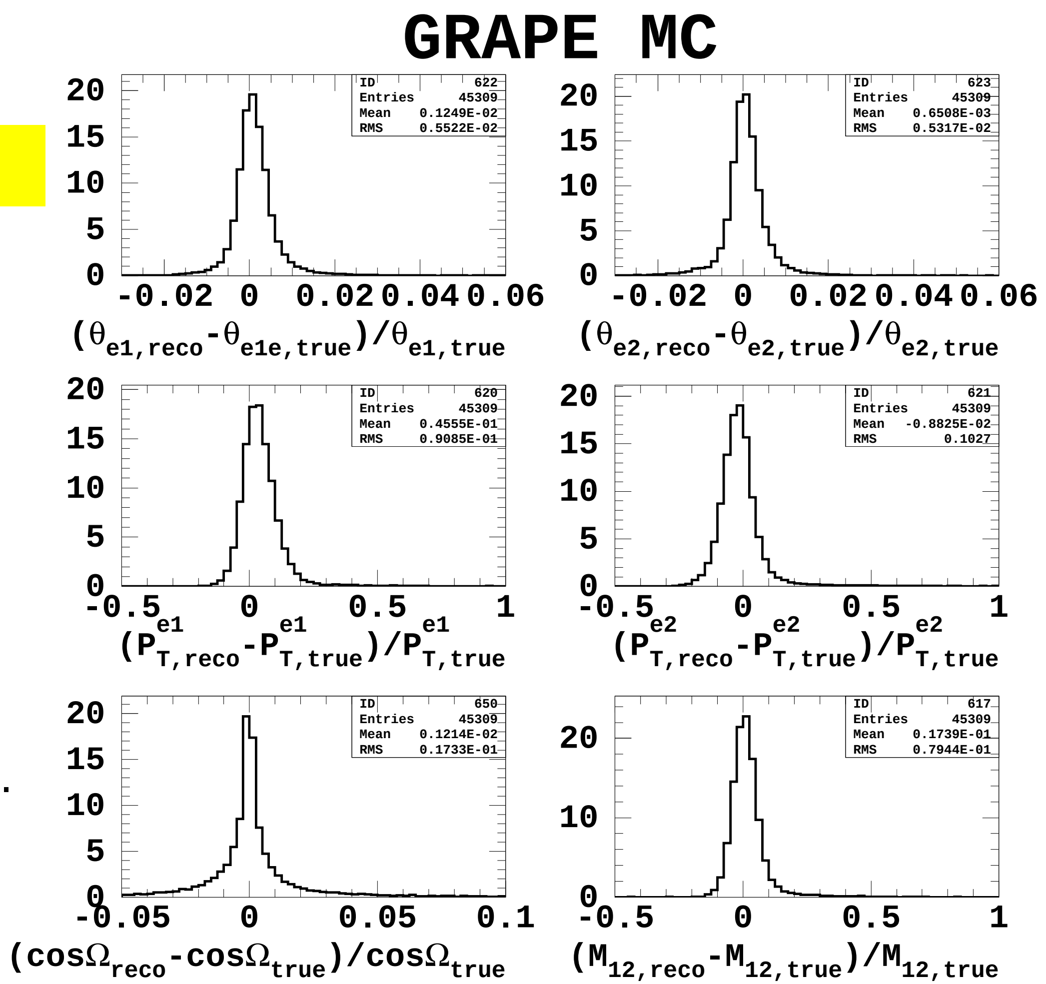
Variable reconstruction

Resolutions:

- $\sigma(\theta)/\theta = 0.5\%$;
- $\sigma(P_T)/P_T = 10\%$;
- $\sigma(\cos\Omega)/\cos\Omega = 2\%$;
- $\sigma(M_{12})/M_{12} = 10\%$.

→ Excellent resolution for angles.

→ Good resolution for energies.



Trigger chain

Di-electron chain

- Elastic di-e: good vertex + few CTD tracks + 2 electrons.
- Inelastic di-e: good vertex + 2 electrons + high mass.

Neutral Current DIS chain

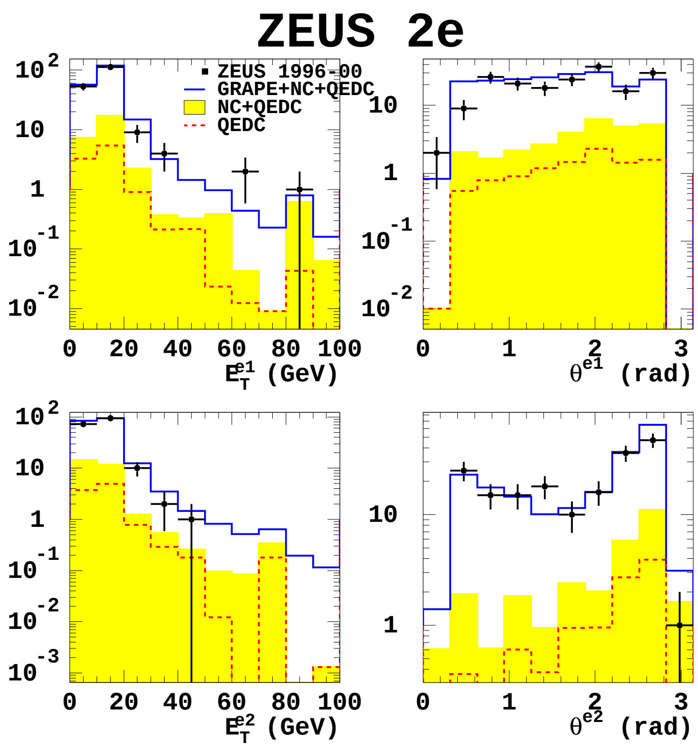
- good vertex + 1 electron + large E_T + large Q^2 + large $E - P_z$.

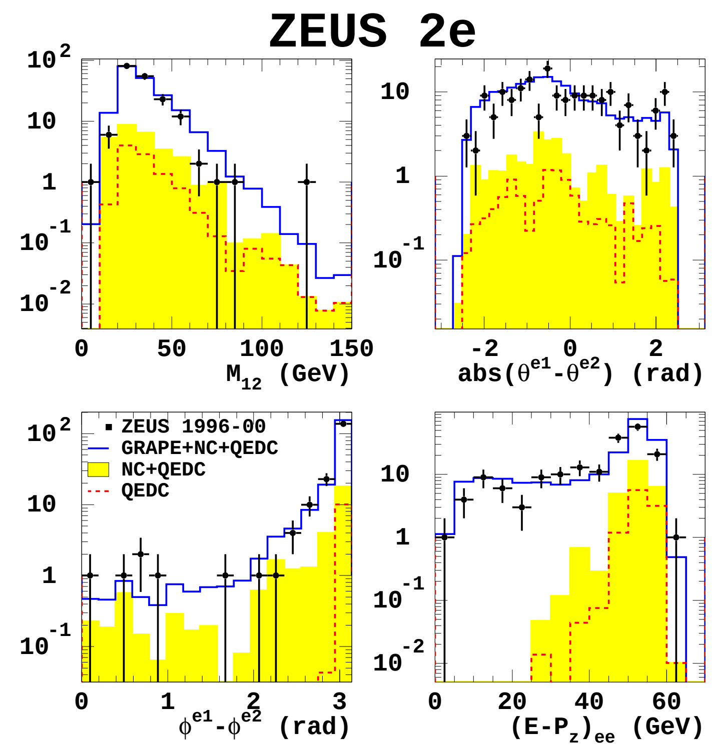
High-E_T chain

- high E_T in the CAL.

Data to MC comparison: $2e$

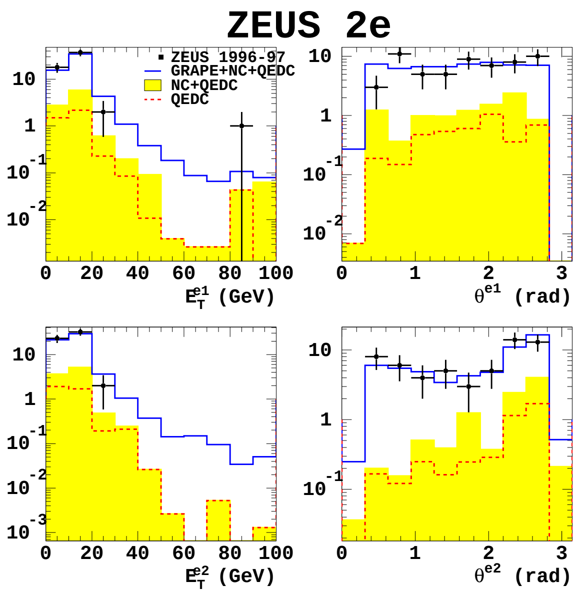
1996-2000 data taking → L=120.49 pb^{-1}					
Selection	Data	All SM	di-ele MC	NC-DIS MC	QED-C MC
All $2e$	183	197.78	169.11	18.57	10.10
$M_{12} > 50$ GeV	17	27.47	22.68	3.32	1.47
$M_{12} > 100$ GeV	1	0.67	0.46	0.08	0.13



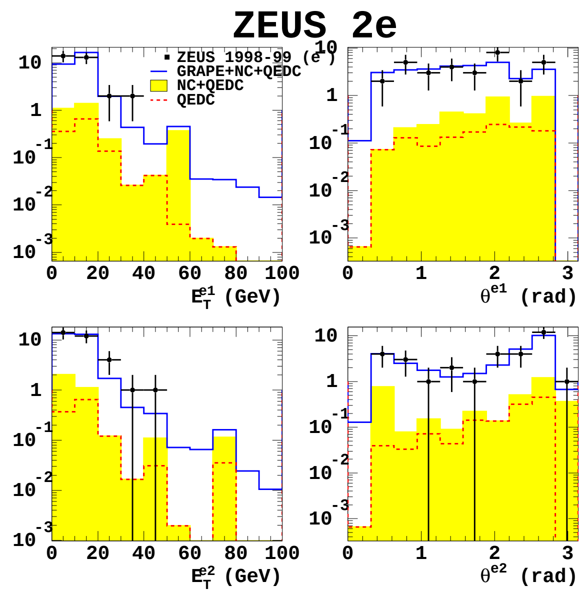


Data to MC comparison: $2e$

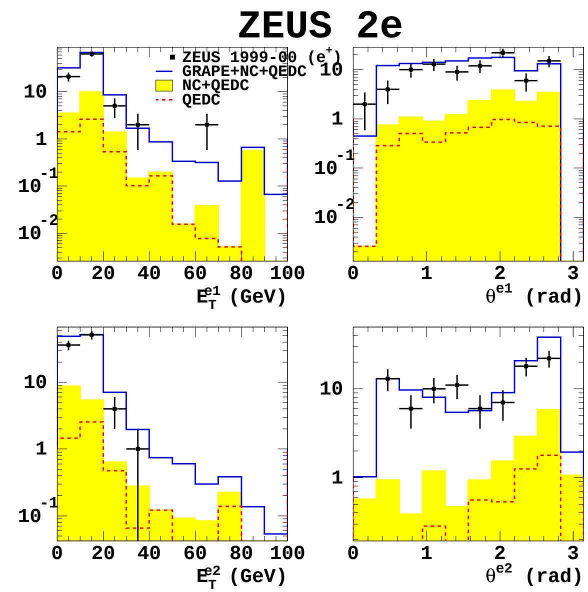
1996-97 period



1998-99 period

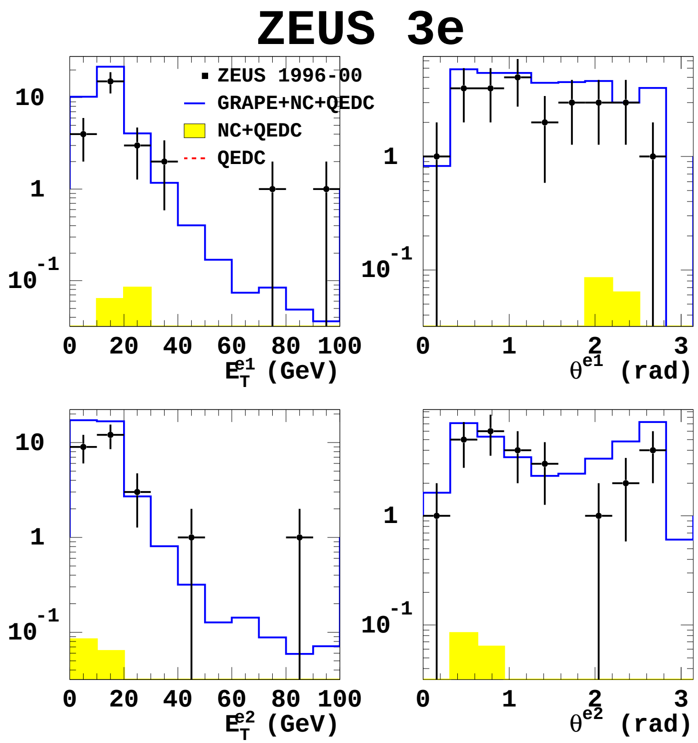


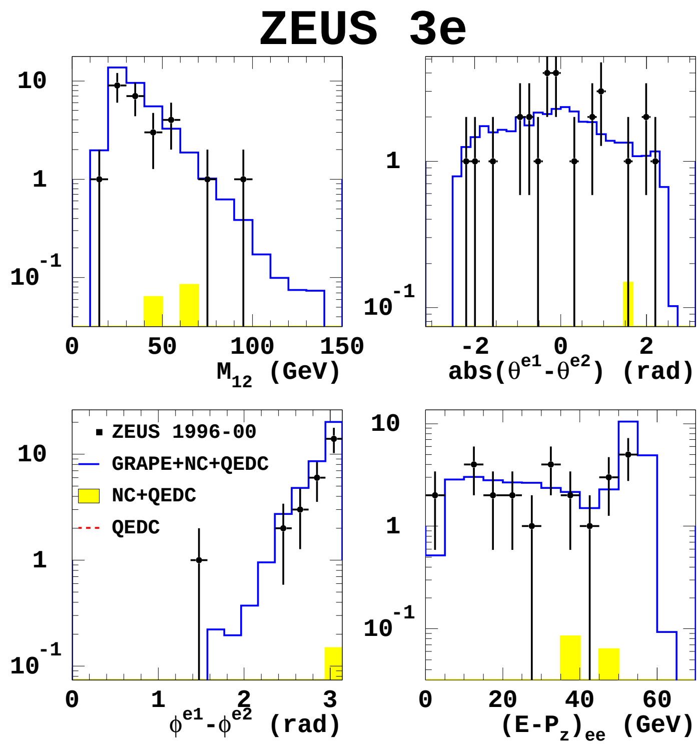
1999-2000 period



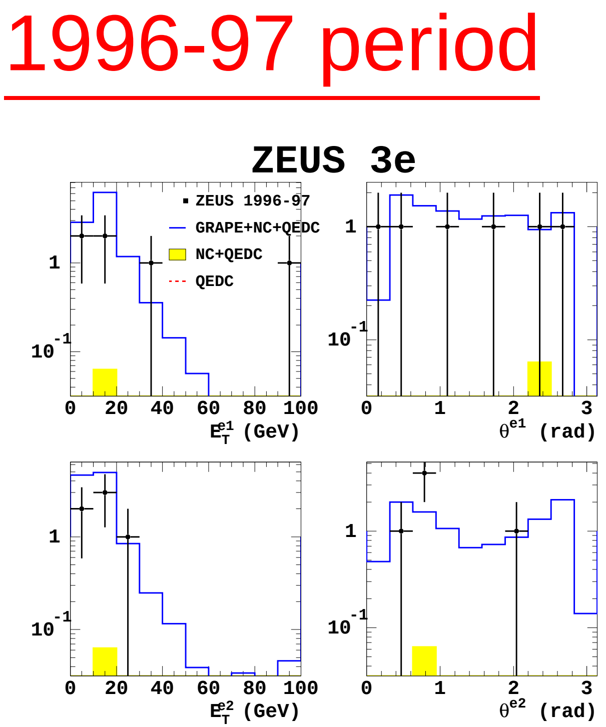
Data to MC comparison: $3e$

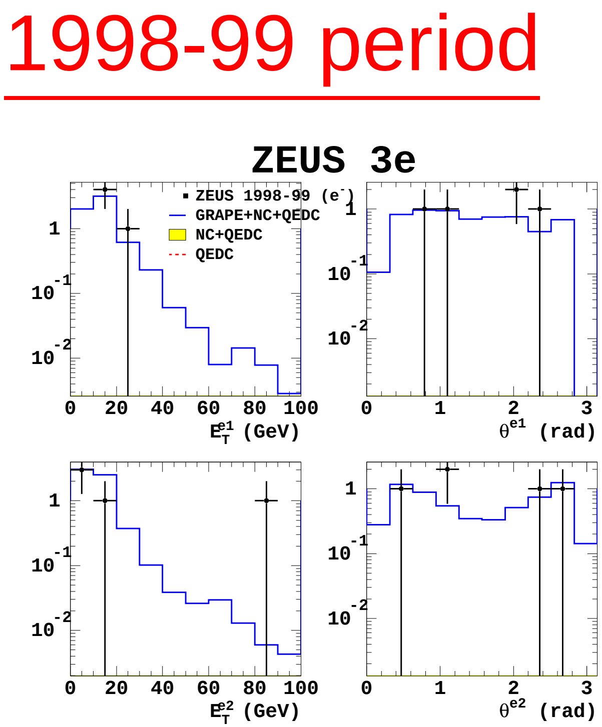
1996-2000 data taking → $L=120.49\ pb^{-1}$					
Selection	Data	All SM	di-ele MC	NC-DIS MC	QED-C MC
All $3e$	26	38.03	37.88	0.15	0.00
$M_{12} > 50$ GeV	6	7.54	7.46	0.08	0.00
$M_{12} > 100$ GeV	0	0.44	0.44	0.00	0.00

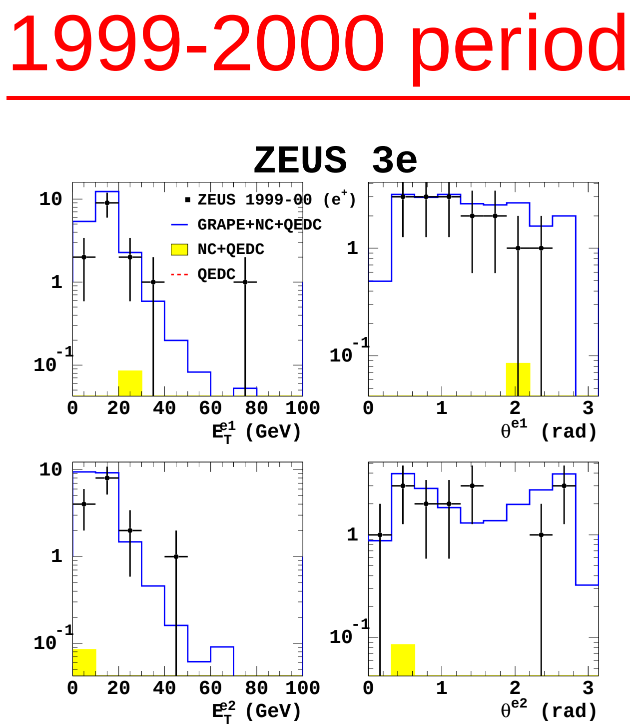




Data to MC comparison: $3e$







Cross section: Method

- N_g: MC events generated;
- N^r: MC events reconstructed;
- N_g^r: MC events generated AND recontsructed;
- N_d: events selected in data.

Definitions

- efficiency: $e = N_g^r / N_g$;
- purity: $p = N_g^r / N_r$;
- acceptance: $a = N^r / N_g$.

Cross section

- Total:

$$\sigma_{\mathrm{MC}} = \frac{N_g}{L}$$

$$\sigma_{\mathrm{DATA}} = \frac{N_d}{L\ a}$$

- Differential:

$$\frac{\mathrm{d}\sigma_{\mathrm{MC}}}{\mathrm{d}x} = \frac{N_g}{L\ \Delta x}$$

$$\frac{\mathrm{d}\sigma_{\mathrm{DATA}}}{\mathrm{d}x} = \frac{N_d}{L\ a\ \Delta x}$$

Cross section: combination of periods

Correction for $\sqrt{s}$

To refer cross-section to $\sqrt{s} = 318$ GeV:

$$\sigma_x^{318} = \frac{\sigma_{99-00}^{\mathrm{MC}}}{\sigma_x^{\mathrm{MC}}} \sigma_x^{\mathrm{DATA}}$$

x = 1996-97 or 1998-99

Combination of periods

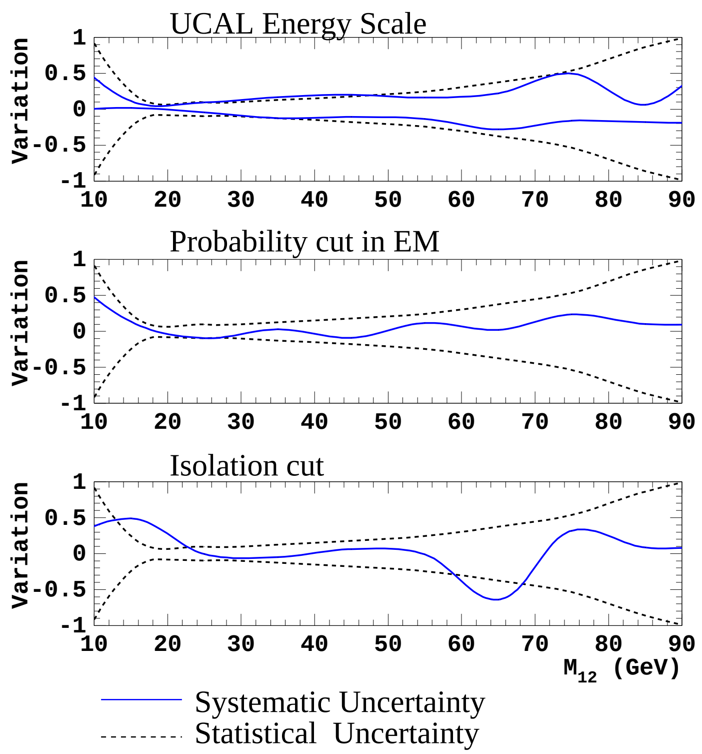
$$\sigma_{96-00} = \frac{\sum_x \sigma_x^{318} \; L_x}{\sum_x L_x}$$

x = 1996-97, 1998-99 or 1999-2000

Systematic uncertainties

Type	Variation	Effect
Lumi measurement	2%	2%
CAL energy scale	5%	$^{+9.4}_{-4.1}$%
Prob. cut in EM	$P_{\rm grand}>0.01\rightarrow0.1$ $P_{\rm cal}>0.1\rightarrow0.2$	-4.8%
Isolation cut	$E_{\rm cone} < 0.3 \rightarrow 0.2$ GeV	$+7.3$%
Mass cut	8%	0%
➔ Total		$^{+13}_{-10}$%

➔ Statistical uncertainty: $\pm 14\%$.



Cross section: Tables

Bin definition	Pur.	Acc.	$\frac{d\sigma_{DATA}}{dx}$ (pb/[x])	$\frac{d\sigma_{MC}}{dx}$ (pb/[x])
$15 < M_{12} < 25$ GeV	0.723	0.309	$(4.2 \pm 1.1 \pm 1.0)$E$-$02	5.7E$-$02
$25 < M_{12} < 40$ GeV	0.840	0.330	$(5.2 \pm 1.0 \pm 0.6)$E$-$02	4.5E$-$02
$40 < M_{12} < 60$ GeV	0.803	0.206	$(1.50 \pm 0.57^{+0.34}_{-0.32})E-$02	1.38E$-$02
$10 < P_T^e < 15$ GeV	1.154	0.223	$(2.20 \pm 0.42^{+0.28}_{-0.20})E-$01	1.94E$-$01
$15 < P_T^e < 20$ GeV	1.073	0.236	$(5.6 \pm 2.1^{+1.1}_{-1.0})E-$02	4.9E$-$02
$20 < P_T^e < 25$ GeV	0.924	0.239	$(1.13 \pm 0.93^{+0.45}_{-0.43})E-$02	1.69E$-$02
$0.349 < \theta_e < 1.105$ rad	0.831	0.381	$(6.6 \pm 1.4^{+1.0}_{-0.9})E-$01	7.2E$-$01
$1.105 < \theta_e < 1.862$ rad	0.828	0.334	$(5.1 \pm 1.4 \pm 0.6)$E$-$01	5.6E$-$01
$1.862 < \theta_e < 2.618$ rad	0.681	0.198	$(8.1 \pm 2.2^{+1.2}_{-1.0})E-$01	6.8E$-$01

Di-muon search

Muon tagging: GLOMU

The GLOMU package tags muons in the barrel/rear region.

It combines info from inner B/RMUON, CTD, CAL.

Sketch of the algorithm:

- CTD tracks with high momentum and close to vertex are collected;
- B/RMUI tracks are collected;
- MIP-like deposits are searched in the CAL;
- a match is attempted in θ-ϕ for these objects;
- a cut $\chi^2 < 20$ is set to accept a match.

Muon tagging: MPMATCH2 and MIPs

The MPMATCH2 package tags muons in the forward region.
It combines info from inner FMUON and CTD.

Sketch of the algorithm:

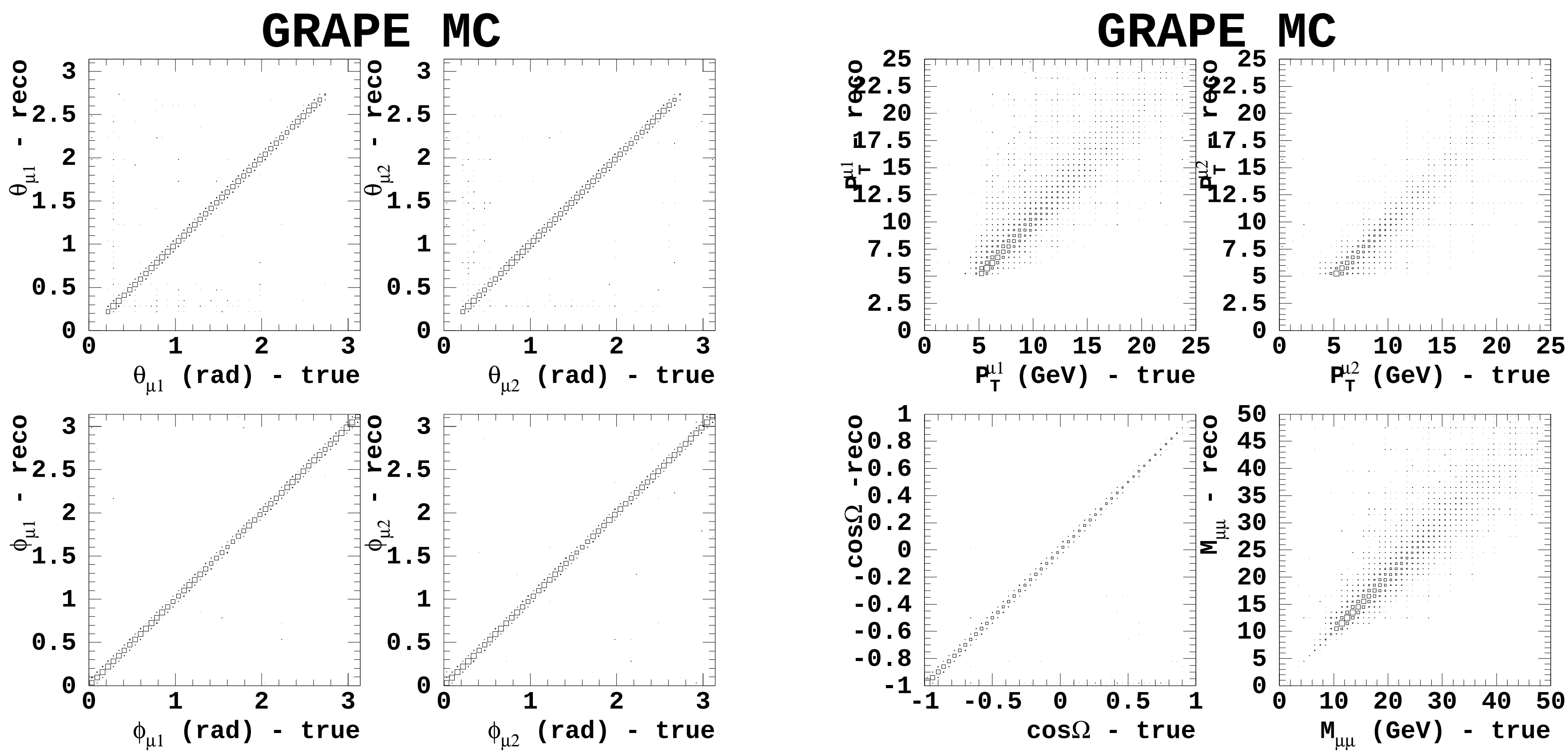
- tracks are reconstructed in the FMU detector;
- these tracks are backwards propagated to the CAL surface;
- CTD tracks are extrapolated to the same surface;
- a match is attempted of the two sets of tracks;
- track parameters are refitted.

To raise efficiency in muon finding, a matching of CTD tracks and MIP-like deposits in the CAL is attempted.

- CTD tracks are extrapolated to the CAL and matched to MIP-like deposits.

Variable reconstruction

Very nice correlation of true and reconstructed variables:



Variable reconstruction

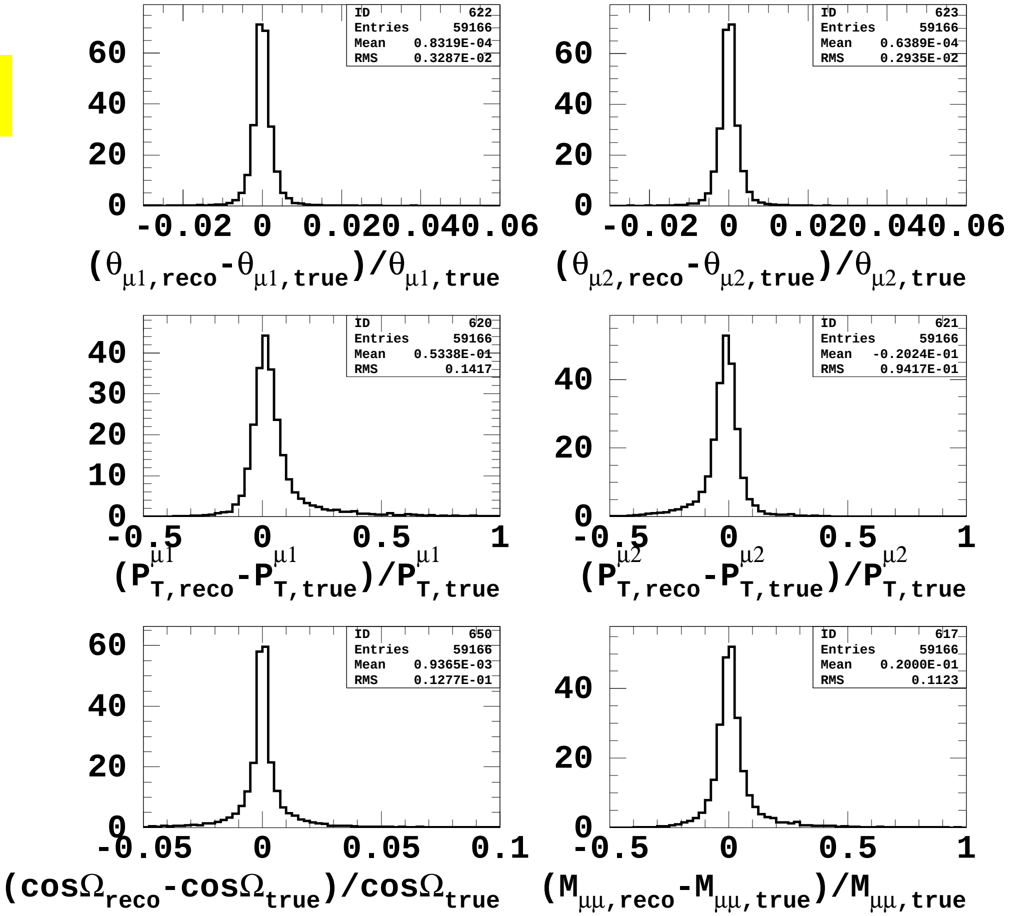
Resolutions:

- $\sigma(\theta)/\theta = 0.3\%$;
- $\sigma(P_T)/P_T = 10 \div 15\%$;
- $\sigma(\cos\Omega)/\cos\Omega = 1\%$;
- $\sigma(M_{\mu\mu})/M_{\mu\mu} = 10\%$.

→ Excellent resolution for angles.

→ Good resolution for energies.

GRAPE MC



Trigger chain

B/RMUON chain

- Inner chambers trigger: (few CTD tracks + B/RMUI signal) OR (B/RMUI signal matched to CTD tracks and MIP-like deposits).
- Outer chambers trigger: Signal in B/RMUI and B/RMUO + CAL activity and CTD tracks
- Both chains: a GLOMU matching

FMUON chain

- few CTD tracks + matching (FMU and MIP-like deposits) + two CTD tracks with high invariant mass

B/RMUI Efficiencies

B/RMU inefficiencies are not simulated in MC

→ Efficiencies were measured (M. Turcato, A. Bertolin, M. Corradi)

Method

Di-muon events are selected (J/ψ, Bethe-Heitler, ...) by

- A hit in muon chambers
- 2 CTD tracks with $M > 2.5$ GeV
- Acollinearity: $\cos\Omega > -0.95$

The efficiency is

$$e = \frac{\text{No. of GLOMU tracks}}{\text{No. of CTD tracks}}$$

Results

The ratio $R = \frac{e(DATA)}{e(MC)}$ is used to weight Monte Carlo samples

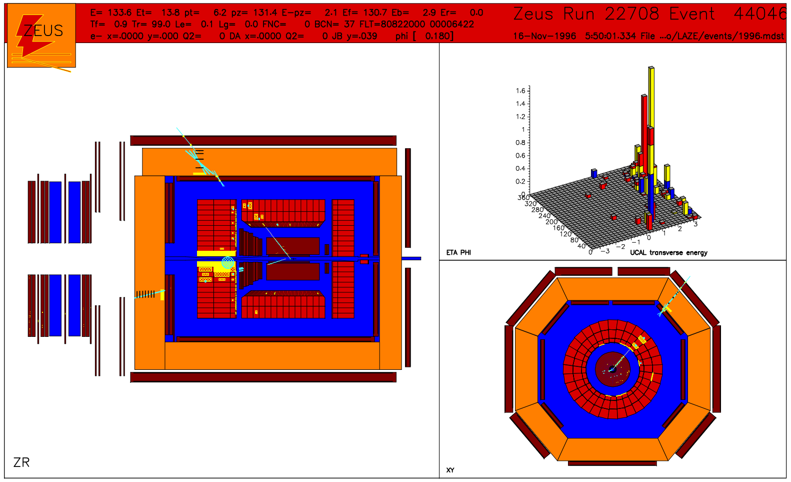
Region	Data/MC ratio	
	Years 1996-97	Years 1998-2000
BMUI	0.854 ± 0.061	0.709 ± 0.042
RMUI	0.819 ± 0.068	0.853 ± 0.050

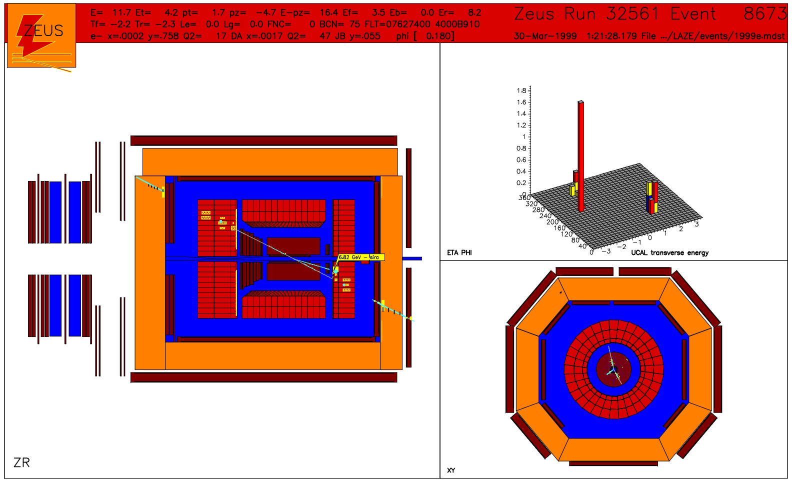
→ BMUI cut: $4.25 < P_T^\mu < 10$ GeV

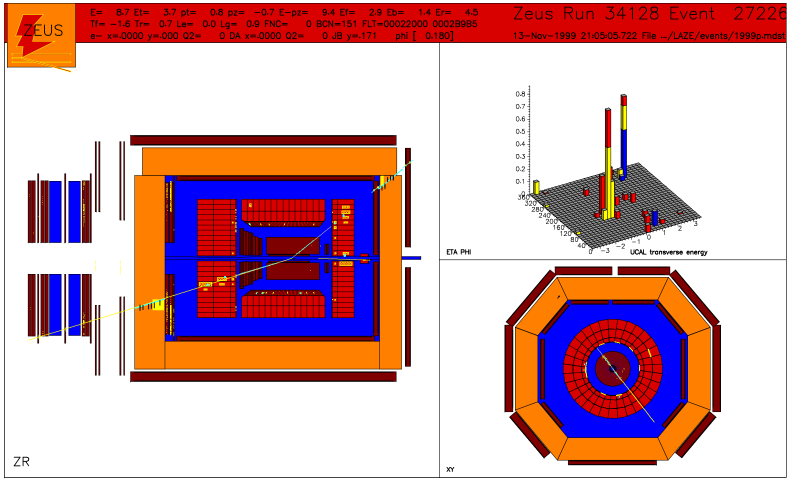
→ RMUI cut: $5 < P_T^\mu < 10$ GeV

Di-muon events

- Three events found around $M_{\mu\mu} = 50\ \mathrm{GeV}$
- All of them look like genuine di-muons



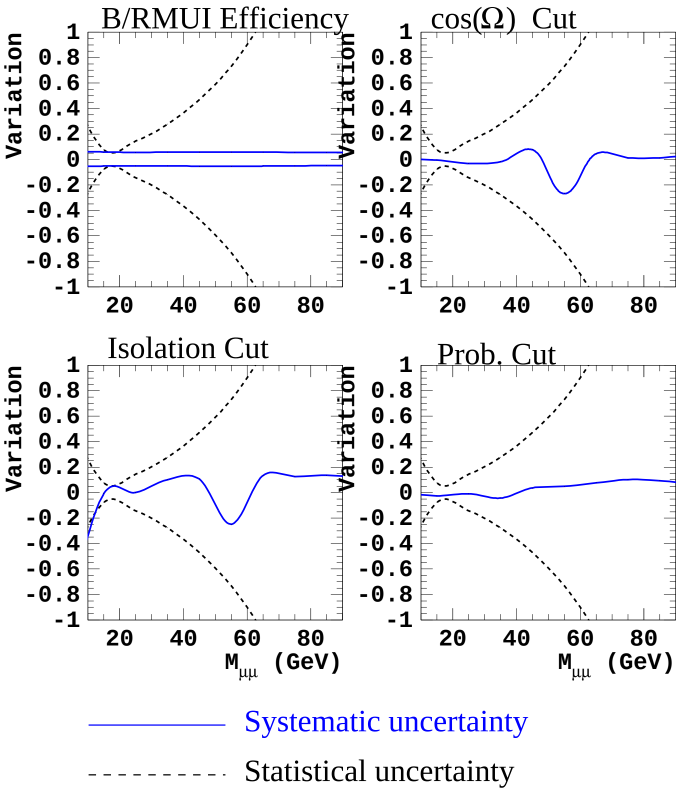




Systematic uncertainties

Type	Variation	Effect
Lumi measurement	2%	2%
B/RMUI Efficiency	7.5% in 1996−97 6.0% in 1998−00	$^{+5.4}_{-4.8}$%
$\cos\Omega$ cut	$\cos\Omega > -0.995 \rightarrow -0.985$	$+2.8\%$
Isolation cut	$D^{\mu}_{\rm Trk} > 1 \rightarrow 2$	$+4.0\%$
Prob. cut	$\chi^2 < 20 \rightarrow 10$ (GLOMU) $P > 0.01 \rightarrow 0.05$ (MPMATCH2)	-0.4%
➡ Total		$^{+7.2}_{-6.6}$%

➡ Statistical uncertainty: $\pm 6.9\%$.

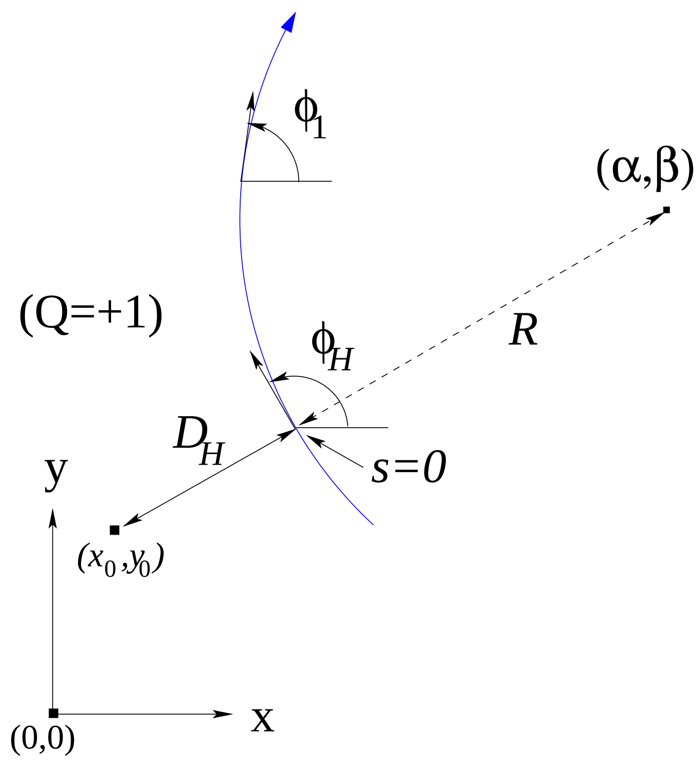


Cross section: Tables

Bin definition	Pur.	Acc.	$\frac{d\sigma_{\mathrm{DATA}}}{dx}$ (pb/[x])	$\frac{d\sigma_{\mathrm{MC}}}{dx}$ (pb/[x])
$10 < M_{\mu\mu} < 20$ GeV	0.968	0.437	$(3.44 \pm 0.28^{+0.24}_{-0.22})$E−01	3.70E−01
$20 < M_{\mu\mu} < 30$ GeV	0.977	0.412	$(8.0 \pm 1.4^{+0.8}_{-0.7})$E−02	10.7E−02
$30 < M_{\mu\mu} < 45$ GeV	0.928	0.388	$(2.02 \pm 0.58^{+0.32}_{-0.31})$E−02	2.40E−02
$45 < M_{\mu\mu} < 100$ GeV	0.787	0.437	$(2.04 \pm 0.91 \pm 0.65)$E−03	1.90E−03
$5 < P_T^{\mu} < 6.5$ GeV	0.949	0.401	$1.53 \pm 0.16^{+0.11}_{-0.10}$	1.55
$6.5 < P_T^{\mu} < 8$ GeV	1.009	0.437	$(7.6 \pm 1.1^{+0.6}_{-0.5})$E−01	8.3E−01
$8 < P_T^{\mu} < 13$ GeV	0.994	0.447	$(2.17 \pm 0.31^{+0.23}_{-0.22})$E−01	2.72E−01
$13 < P_T^{\mu} < 50$ GeV	0.885	0.473	$(7.9 \pm 2.1^{+1.3}_{-1.2})$E−03	10.3E−03
$0.262 < \theta_{\mu} < 0.912$ rad	0.963	0.339	$2.36 \pm 0.42^{+0.18}_{-0.17}$	2.81
$0.912 < \theta_{\mu} < 1.562$ rad	0.977	0.523	$1.65 \pm 0.22^{+0.13}_{-0.12}$	1.83
$1.562 < \theta_{\mu} < 2.212$ rad	0.970	0.516	$1.83 \pm 0.23^{+0.14}_{-0.13}$	1.69
$2.212 < \theta_{\mu} < 2.862$ rad	0.963	0.385	$1.41 \pm 0.24^{+0.14}_{-0.13}$	1.84

MVD tracking at ZEUS TLT

Track parameterisation



Coordinates

$$x(\phi) = x_0 + \left(a_3 + \frac{1}{a_2}\right)\sin a_1 - \frac{\sin\phi}{a_2}$$

$$y(\phi) = y_0 - \left(a_3 + \frac{1}{a_2}\right)\cos a_1 + \frac{\cos\phi}{a_2}$$

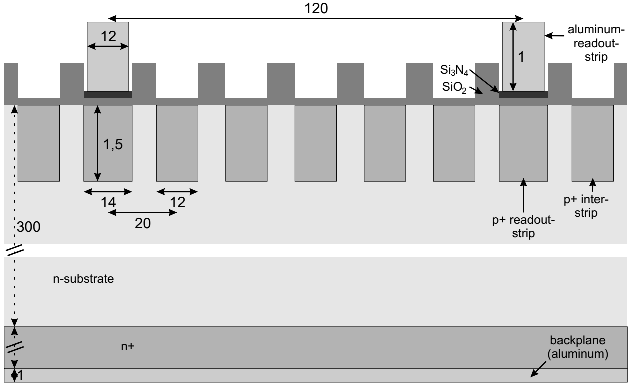
$$z(\phi) = a_4 - \frac{a_5}{a_2}\left(\phi - a_1\right)$$

Pathlegth

$$s = -\frac{\phi - a_1}{a_2}$$

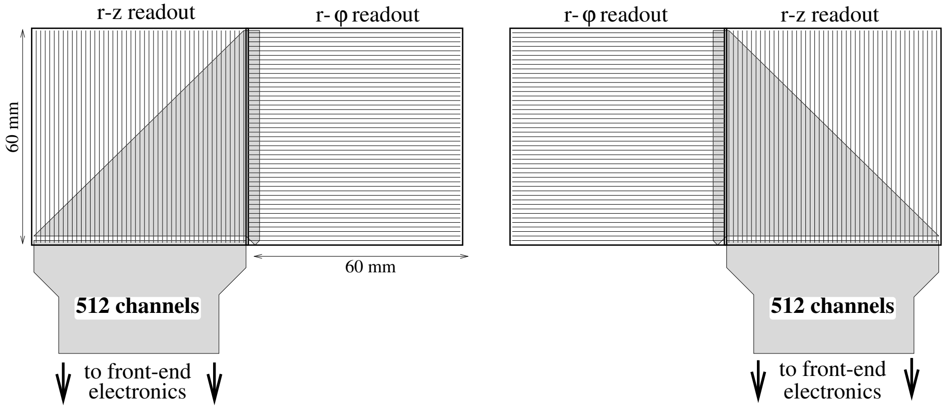
The ZEUS MVD: design

Sensor design



- 64x64 mm n-type silicon sensors
- p^+ strips every 20 μm
- a strip over 6 is read-out

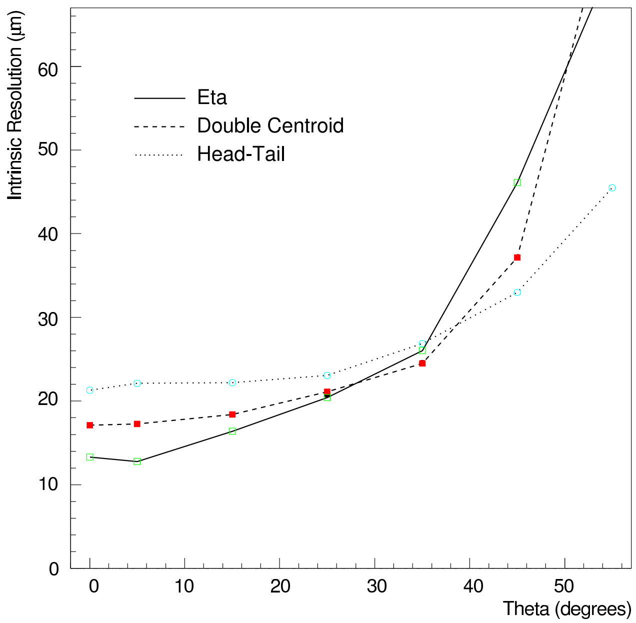
BMVD design



- Two sensors form a "half-module"
- Two half-modules form a "module", 2.2% X_0 thick
- A module measures $r\phi$ and z coordinates

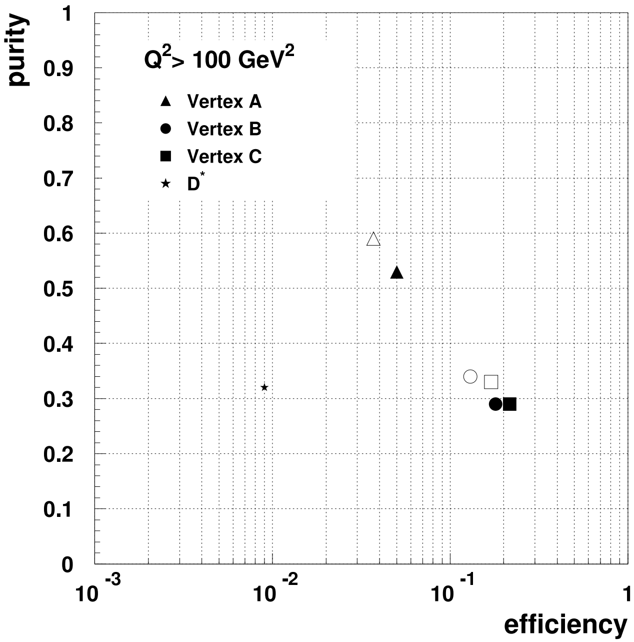
The ZEUS MVD: performances

Test beam



Cluster resolution on a single detector (6 GeV beam), with different reconstuction algorithms.

Example: c-quark selection



→ Using D^* tagging:

eff $\simeq$ 1% @ pur $\simeq$ 30%

→ Using MVD (simulation):

eff $\simeq$ 10–20% @ pur $\simeq$ 30%

The clustering procedure

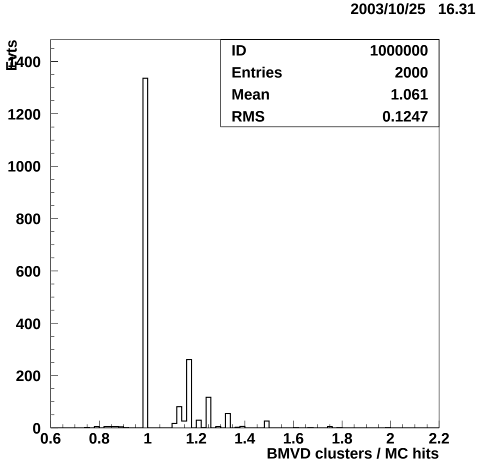
Procedure

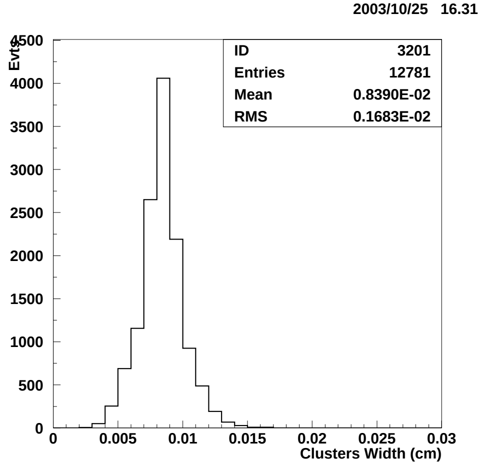
- Pedestal and common mode are subtracted;
- Consecutive strips above threshold are clustered;
- Centre and width: accordingly to centre of gravity:

$$\langle \xi \rangle = \frac{1}{Q} \sum_i Q_i \xi_i$$

$$\sigma^2(\xi) = \frac{1}{Q} \sum_i Q_i (\xi_i - \langle \xi \rangle)^2$$

Results





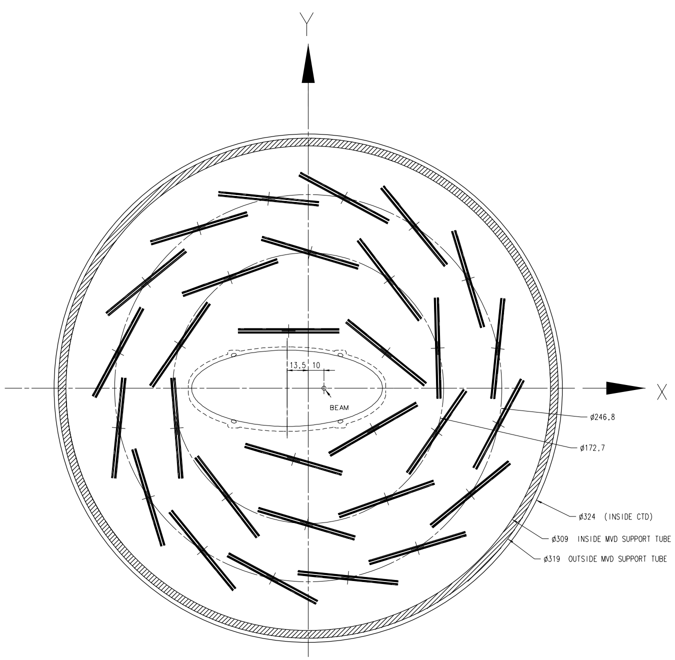
➡ Left: Eff =

(No. of meas. hits)/(No. of GEANT hits)

➡ Right: Cluster widths

➡ Results obtained on a single μ MC

Multiple scattering



Dead materials:

- Ladders (rectangular boxes);
- Support tube (cylinder);
- Beam pipe (ellipsoidal cylinder).

➡ D is the traversed material (g/cm^2)

Scattering angle

$$\delta_{2D} = \frac{0.0136}{p/\mathrm{GeV}} \sqrt{D}\,(1 + 0.0038 \ln D)$$

$$\delta_{\mathrm{RMS}} = \frac{\delta_{2D}}{|\sin\theta|}$$

Effect on covariance matrix

$$\mathrm{cov}(a_1, a_1) \rightarrow \mathrm{cov}(a_1, a_1) + \delta^2_{\mathrm{RMS}}$$

$$\mathrm{cov}(a_1, a_3) \rightarrow \mathrm{cov}(a_1, a_3) + Q\ s\ \delta^2_{\mathrm{RMS}}$$

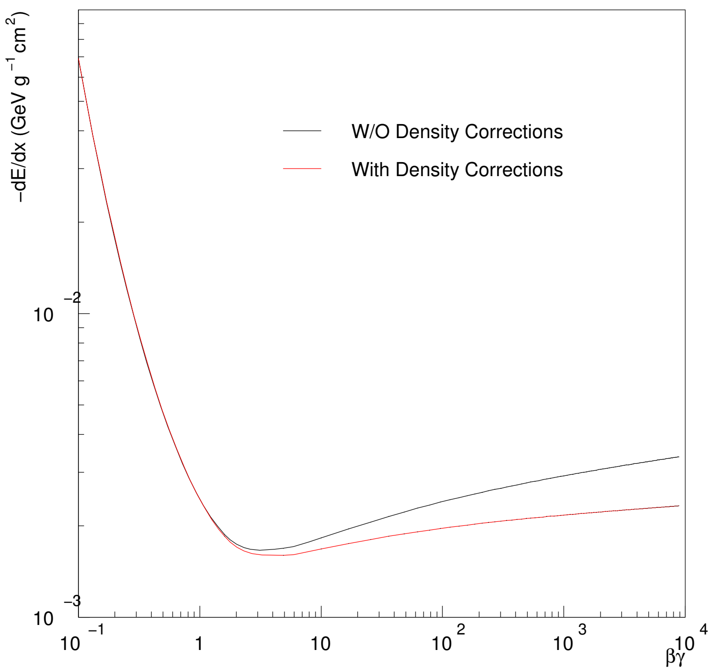
$$\mathrm{cov}(a_3, a_3) \rightarrow \mathrm{cov}(a_1, a_3) + (s\ \delta_{\mathrm{RMS}})^2$$

➡ Minor effect on the other covariances

Energy loss

Bethe-Bloch Formula:

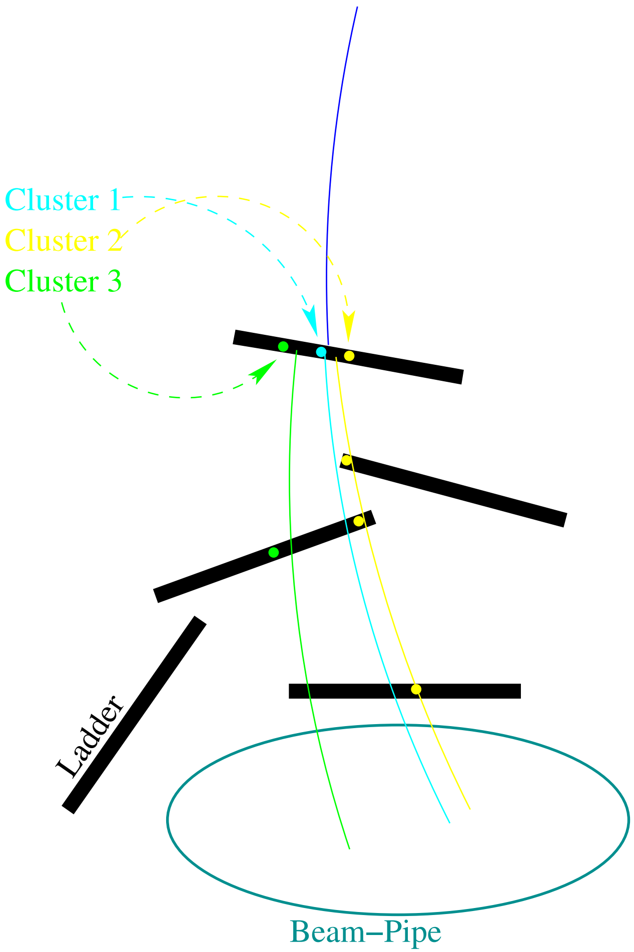
$$-\frac{\mathrm{d}E}{\mathrm{d}x} = Kz^2\frac{Z}{A}\frac{1}{\beta^2}\left[\frac{1}{2}\ln\frac{2m_ec^2\beta^2\gamma^2T_{\max}}{I^2} - \beta^2 - \frac{\delta}{2}\right]$$



where:

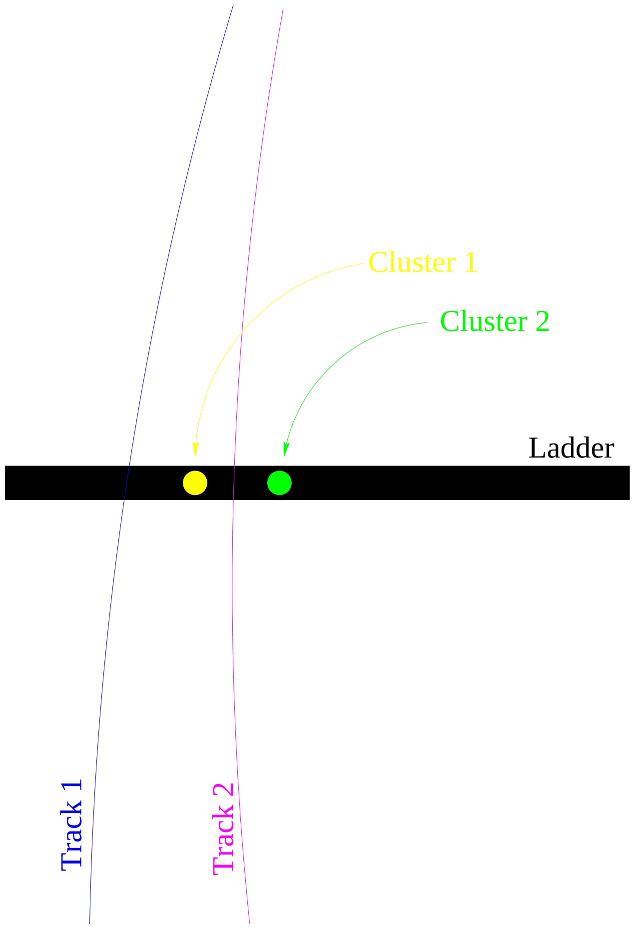
- $K = 3.07075 \cdot 10^{-4}$ GeV cm^2 mol^{-1}
- Incident particle:
  - z is the charge number
  - M is the mass
  - βc is the particle speed
  - $\gamma = 1/\sqrt{1-\beta}$
  - $T_{\max} = \frac{2m_ec^2\beta^2\gamma^2}{1+2\gamma m_e/M}$
- Medium:
  - Z/A: atomic / mass number
  - I is the mean excitation energy
  - δ is the density effect correction

Pattern Recognition



- Each helix is propagated inwards;
- intersections with ladders are found;
- the closest BMVD hit is collected;
- track parameters are updated;
- the procedure is iterated for the remaining layers;
- external layer only: hits are preferrd which leads to hits in the internal layers.

Multiple assignment



- The same hit may be assigned to more tracks.
- If one hit is present:
  - hit is assigned to the closest track
- If two or more hits are present:
  - assignment is done to minimise $(\mathrm{Trk}_1 - \mathrm{Clu}_n)^2/\sigma^2 + (\mathrm{Trk}_2 - \mathrm{Clu}_m)^2/\sigma^2$

Parameter Fit

Measurement

- $F_m \pm \sigma_m$: measurement No. m
- $f(m; \vec{a})$: expected position

Before fit

➔ χ_0^2 of old fit (minimised wrt $\vec{a}$).

➔ A measurement F_m is added.

- $\chi^2(\vec{a}) = \chi_0^2 + \frac{[F_m - f(m;\vec{a})]^2}{\sigma_m^2}$
- $B_\mu(\vec{a}) = -\frac{1}{2}\frac{\partial \chi^2(\vec{a})}{\partial a_\mu}$
- $U_{\mu\nu}(\vec{a}) = -\frac{B_\mu(\vec{a})}{\partial a_\mu}$

➔ $\chi^2(\vec{a})$ is no more minimised.

χ^2 Minimisation

Parameter $\vec{a}$ is updated by minimising χ^2: $\frac{\partial \chi^2(\vec{a}+\delta\vec{a})}{\partial a_\mu} = 0$

➔ $\delta a_\mu = U_{\mu\nu}^{-1}(\vec{a})\ B_\nu(\vec{a})$

After fit

- $\vec{a}_{\text{new}} = \vec{a} + \delta\vec{a}$;
- $B_\mu(\vec{a}_{\text{new}}) = 0$;
- $U_{\mu\nu}(\vec{a}_{\text{new}}) = U_{\mu\nu}(\vec{a})$;
- $\chi^2(\vec{a}_{\text{new}}) = \chi^2(\vec{a}) - B_\mu(\vec{a})\delta a_\mu$.