Measurement of the t-dependence in exclusive photoproduction of $\Upsilon(1S)$ mesons at HERA

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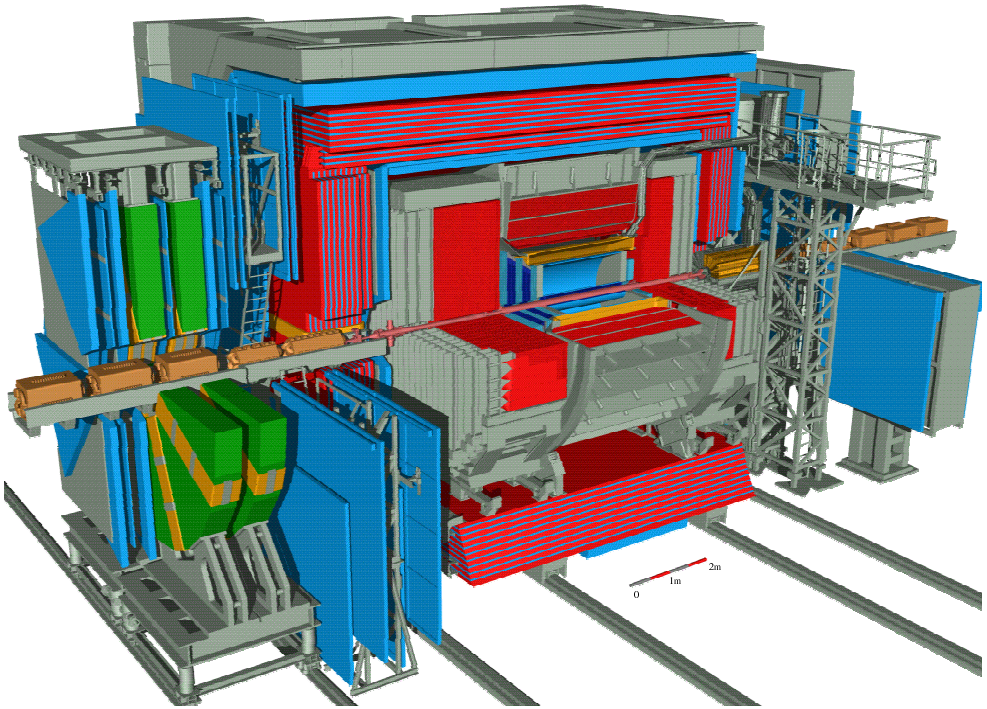
The ZEUS Detector at the HERA *ep* Collider in DESY (Hamburg)

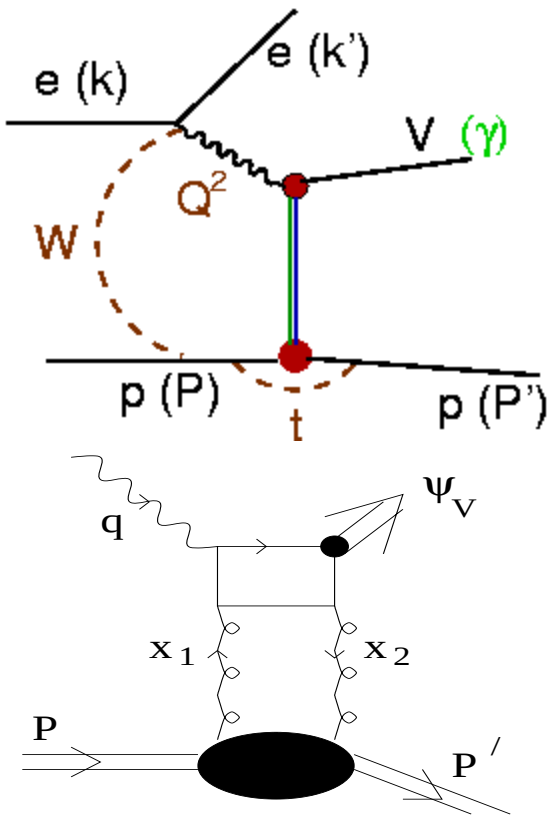


- HERA operated in years 1992-2007
- e^+p and e^-p modes
- $E_e = 27.5$ GeV, $E_p = 920$ GeV
- $E_{CMS} = 318$ GeV
- ZEUS collected $\int L = 468$ pb^{-1}

Detector components used in this analysis:

- MVD: Microvertex Detector
- CTD: Central Tracking Detector
- CAL: Uranium Calorimeter
- BAC: Backing Calorimeter
- F/B/R/MUON: Muon Chambers

Production of Vector Mesons in Exclusive Diffraction in *ep* Scattering



Kinematics of the exclusive process

The proton stays intact !

Kinematics: $\mathbf{M_V^2}$, $\mathbf{Q^2}$, $\mathbf{W}$, $|\mathbf{t}|$

M_V^2 - vector meson mass squared

Q^2 $(= -q^2)$ - the photon virtuality

(emitted by the incoming electron):

- $Q^2 \approx 0$ GeV^2 PHP (*Photoproduction*)
- larger Q^2 for DIS (*Deep Inelastic Scattering*)

W - invariant mass of the γp system

$W^2 = (q + P)^2 \; = \; 2E_p(E - p_z)_V$

Process sensitive to the **gluon longitudinal momentum** in the proton

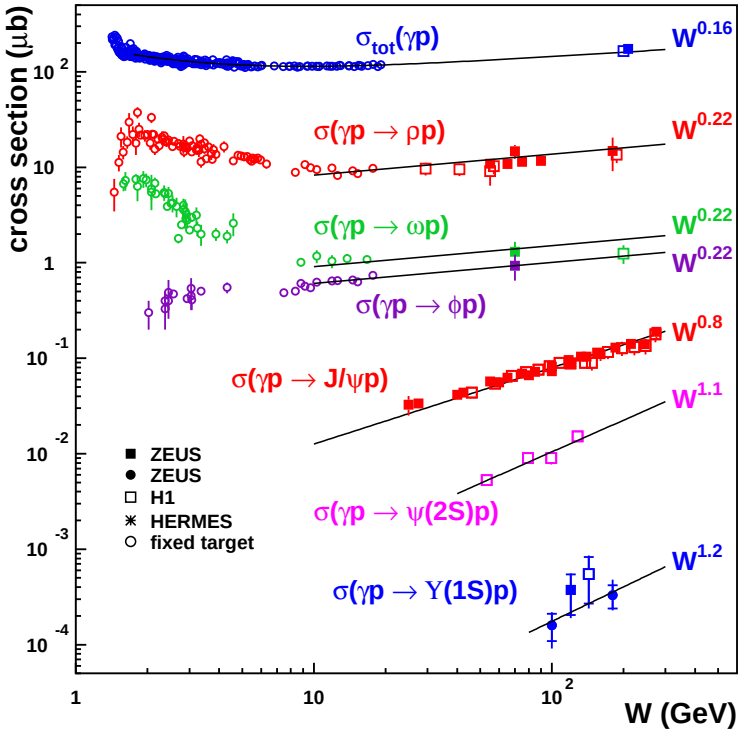
$|t|$ - 4-momentum transfer at the proton vertex

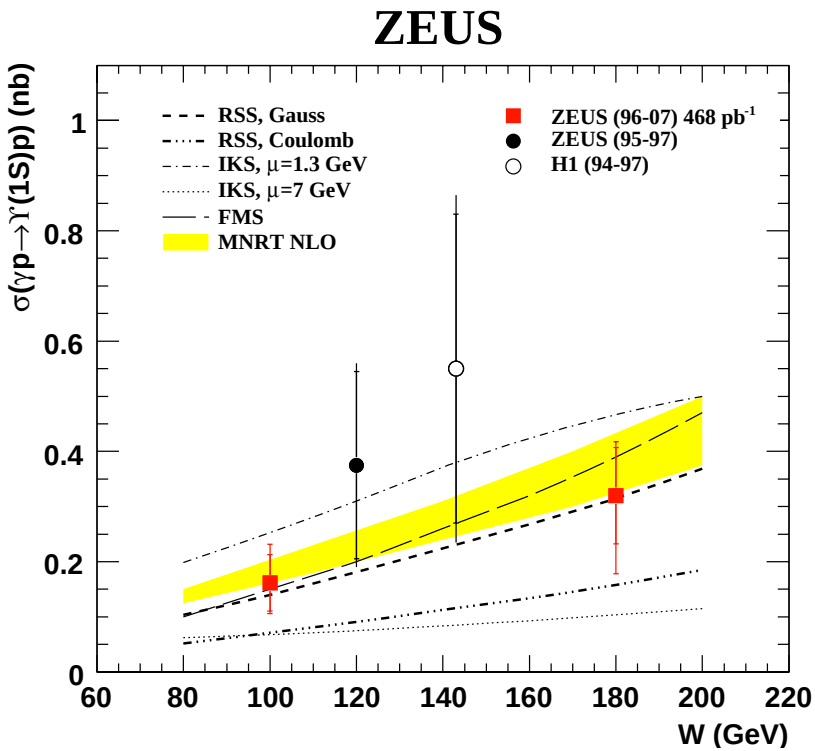
$|t| = |P' - P|^2 \approx p_{TV}^2$ (approx. true, if $p_{Te}^2 \lesssim 1$ GeV^2)

The cross section $\frac{d\sigma}{d|t|} \sim e^{-b|t|}$, b - gives access to the **transverse distribution of the gluons** in the proton

pQCD: M_V^2 and Q^2 - set the scale at which the W and $|t|$ are probed

W-dependence of the VM exclusive cross section for PHP: $\sigma(\gamma p \to Vp)$





$\sigma \sim W^{\delta}$, δ rises with M_V^2 from "soft" ($\delta = 0.22$) to "hard" ($\delta \approx 1.0$)
(expected in QCD from the gluon behavior in the proton)

previous ZEUS measurement of Υ meson: $\delta = 1.2 \pm 0.8$ (Phys. Lett. **B 680**, 4 (2009))

- Υ: sensitive to vector meson wave function: seems to prefer Gauss to Coulomb,
- Υ: sensitive to hard scale value: NRQCD NLO scale is between $1.3 < \mu < 7$ GeV,
- Υ: pQCD models W-slope: FMS LO (δ=1.7), other NLO give value $\delta \approx$1.2

Overview of t-dependence for Vector Mesons

$$\frac{d\sigma}{d|t|} \propto \exp(-b|t|)$$

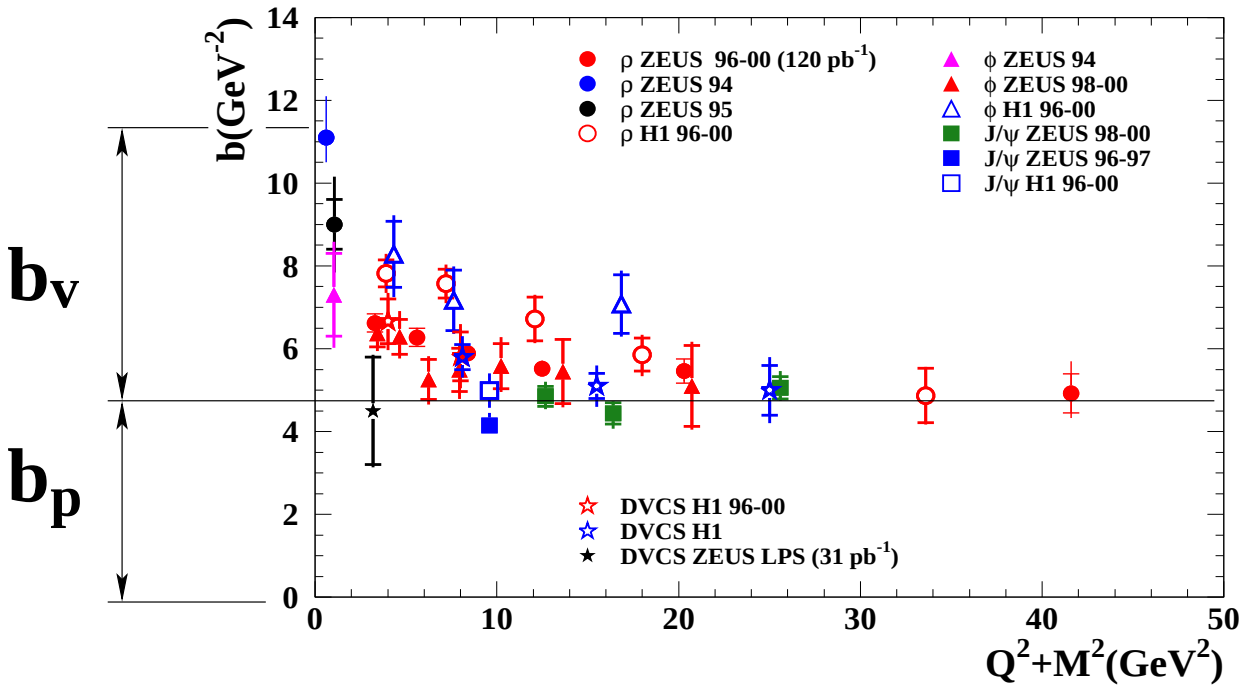
Geometric picture - transverse size:

$b = b_V + b_p$

Vector Meson tr. size:

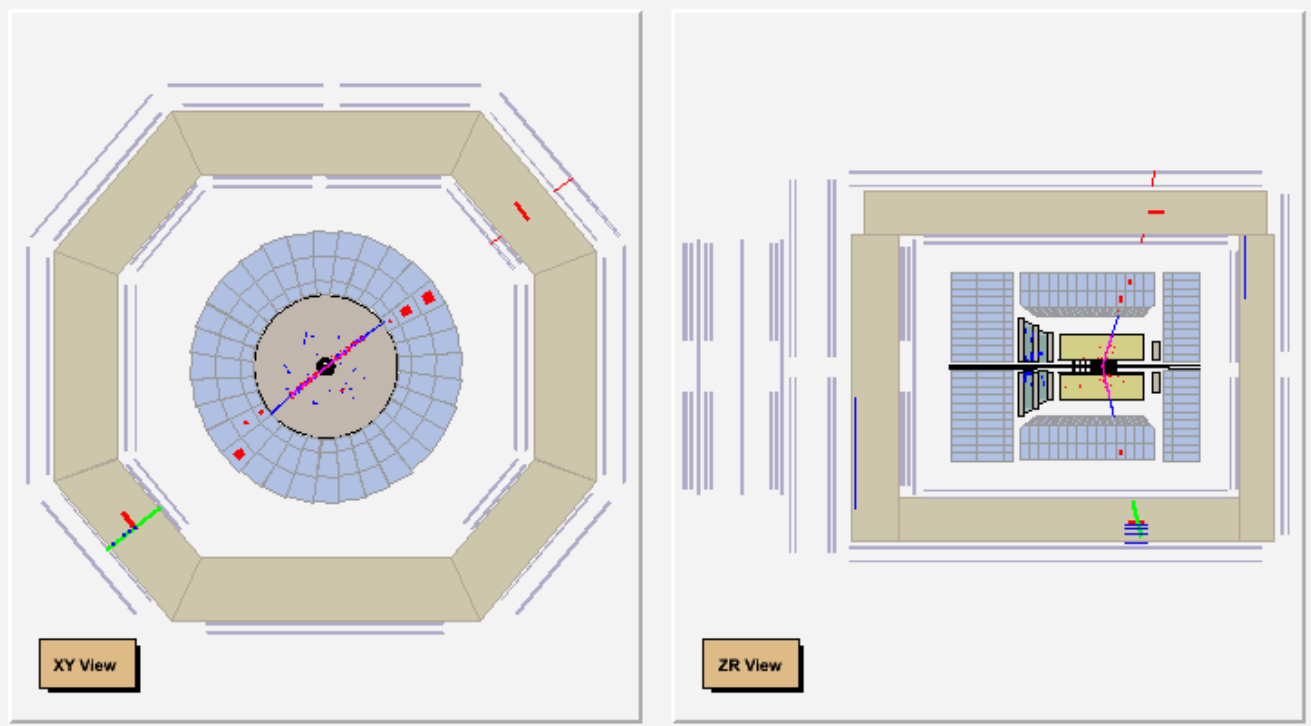
$b_V \sim \frac{1}{Q^2+M_V^2}$

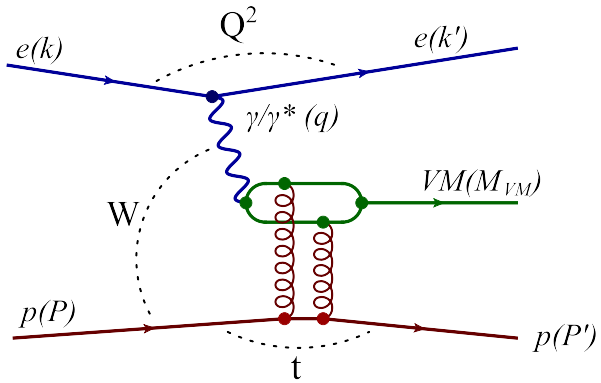
Target (proton) tr. size:
$b_p \approx 5 GeV^{-2}$
can be interpreted as
$r_{gluons} \approx 0.6$ fm
charge radius of the proton
$r_{em} \approx 0.8$ fm



The t-slope, **b**, decreases with the scale $Q^2 + M_V^2$

Final State Topology for $ep \to \Upsilon p$, $\Upsilon \to \mu^+\mu^-$



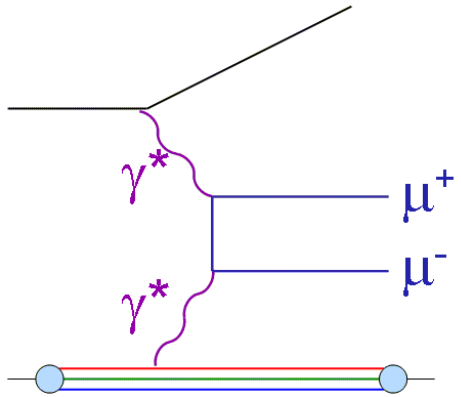


Elastic process, reaction mediated by exchange of colourless object.
Two gluons in LO QCD or Pomeron in Regge theory.

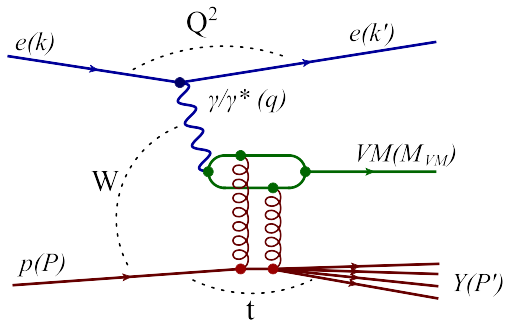
Υ mesons are detected in the $\mu^+\mu^-$ decay channel
very clean final state topology: two muons and nothing else !

Background Sources

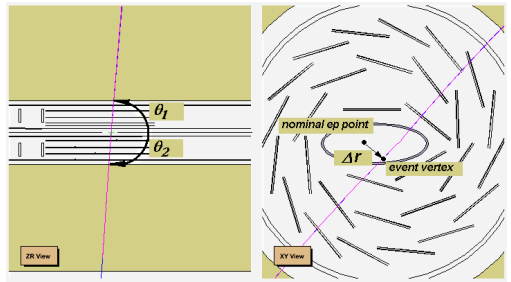
- QED di-muons (like $\gamma^*\gamma^* \to \mu^+\mu^-$) from the Bethe-Heitler process



- Υ mesons production with the dissociation of the proton

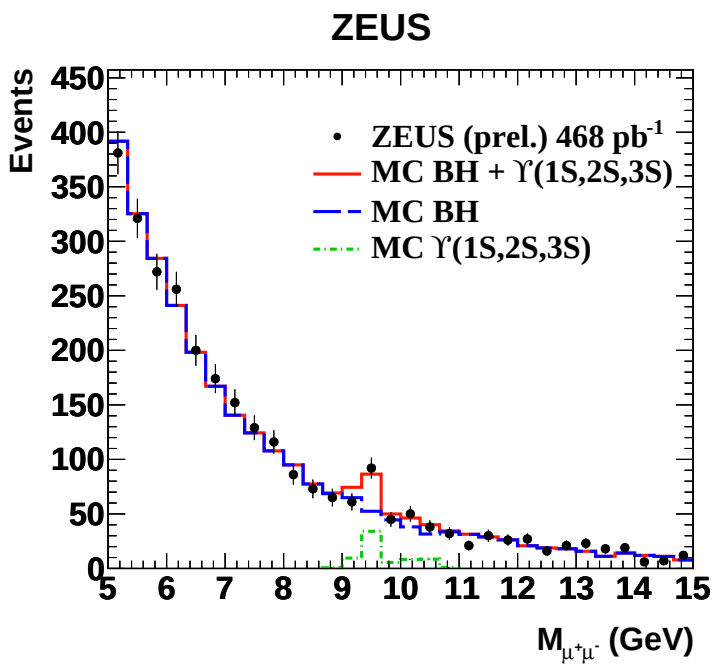


- Cosmic muons can mimic $\mu^+\mu^-$ pairs when passing close to the interaction point



Event Selection

- Muon Triggers (F/B/R/MUON or BAC)
- Tracking and Vertex
  - exactly two, long, oppositely charged tracks matched to the primary vertex
  - $p_T > 1.5$ GeV of each track
  - $|\eta^+ - \eta^-| < 1.5$; to suppress Bethe-Heitler background
  - $|\pi - \alpha| > 0.1$; (anti-collinearity), $\alpha = \angle(\vec{p}^+, \vec{p}^-)$; to further reject cosmic-ray events
  - both tracks identified as a muon (F/B/R/MUON, BAC; 2^{nd} muon at least as CAL MIP)
- Elasticity and Photoproduction cuts (on CAL Energy)
  - $E_{\mathrm{clu}} < 0.5$ GeV for clusters not matched to muon (corresponds to an effective cut on $Q^2 < 1$ GeV^2)
  - $E_{\mathrm{ir}} < 1$ GeV the sum of the energy in the FCAL around the beam hole; to suppress proton-dissociative events, $ep \to e\Upsilon Y$ (corresponds to a requirement for $M_Y \lesssim 4$ GeV)
- Kinematic range:
  - $Q^2 < 1$ GeV^2 (median $Q^2 \approx 10^{-3}$ GeV^2)
  - $60 < W < 220$ GeV
  - $0 < |t| < 5$ GeV^2
  - $5 < M_{\mu^+\mu^-} < 15$ GeV



Monte Carlo Simulation: Υ Resonances Signal

DIFFVM generator - simulate Vector Meson (J/ψ, Υ) production and decay,

- based on Regge phenomenology and Vector Dominance Model
- both the elastic and p.diss production of the Vector Mesons
- assumes S-Channel Helicity Conservation (SCHC)

reproduces shape of:

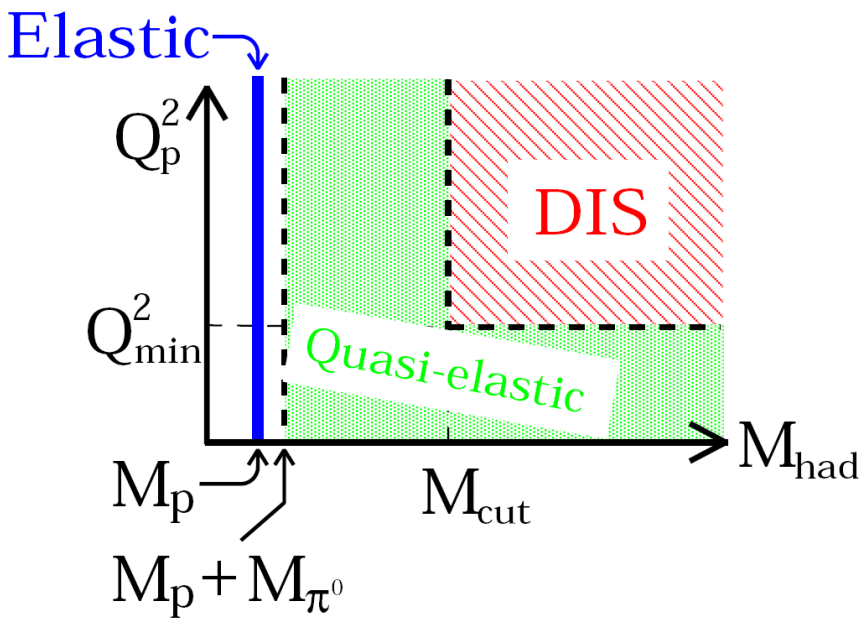
$\rightarrow \sigma \sim W^{\delta}$, where $\delta = 4(\alpha_0 - 1)$

$\rightarrow \frac{d\sigma}{d|t|} \sim e^{-b|t|}$, $b = b_0 + \alpha'(ln\frac{W}{W_0} + ln\frac{M_X}{M_0})$, where $ln\frac{M_X}{M_0}$ - for p.diss

Phenomenology $\rightarrow$ no absolute normalisation, correct kinematics

Monte Carlo Simulation: Bethe-Heitler Background ($\mu^+\mu^-$ Continuum)

GRAPE generator - simulate QED lepton pair (Bethe-Heitler)



Important for the shape of the BH $M_{\mu^+\mu^-}$ spectrum (sidebands)

and for the BH t-dependence: low t - elastic BH, higher t - QEL BH

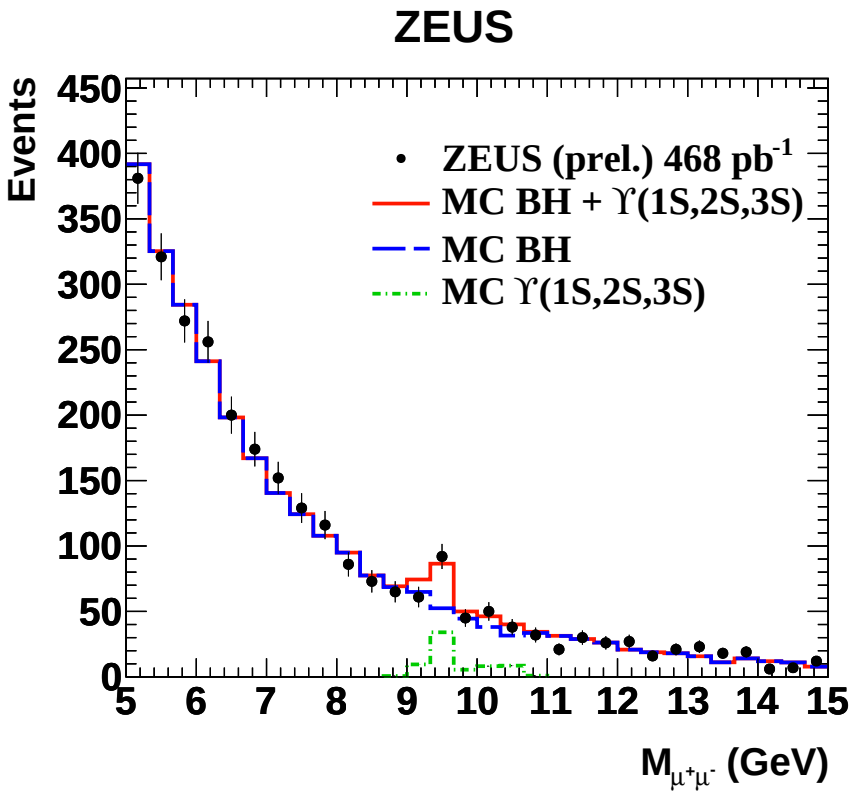
Contribution of the Proton Dissociative Background

- After all elasticity cuts we still see a mixture of elastic + p.diss events,
  - $f_{pdiss} = \frac{p.diss}{ela+p.diss} = ?$
  - has to be determined experimentally
  - this Υ analysis has too small statistic
- it has been shown (ZEUS-2000: Eur. Phys. J. **C 14**, 213) that f_{pdiss} is similar for all Vector Mesons in diffractive production
- relative contribution also does not depend on event kinematics
- we assume $f^{\Upsilon}_{pdiss} = f^{J/\psi}_{pdiss} = 0.25 \pm 0.05$

$\frac{d\sigma}{d|t|} \sim e^{-b|t|}$, has two components:

- elastic: $b = b_{el} \approx 4 \div 12$ GeV^{-2}, depends on M_V^2, Q^2
- p.diss: b_{pdiss} similar for all heavy Vector Mesons, we assume $b_{pdiss} \approx 0.65$ GeV^{-2} as for ZEUS J/Ψ analysis (Eur. Phys. J. **C 24**, 345)

Υ Signal Extraction: $M_{\mu^+\mu^-}$ Spectrum



Signal $N_{\Upsilon(1S)}$ estimated from:

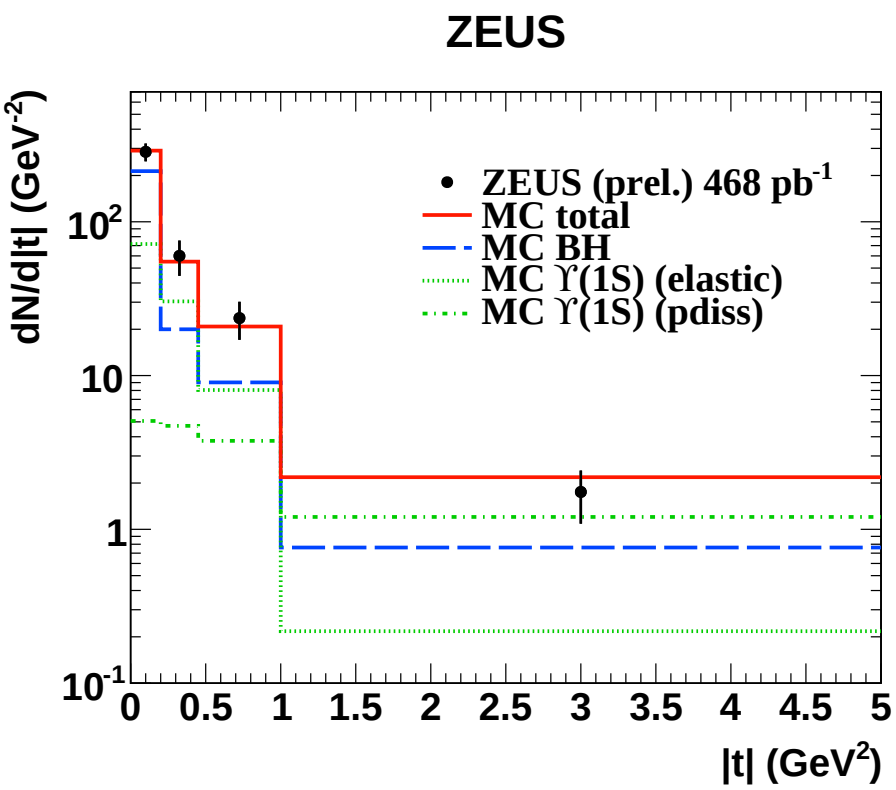
- MC templates fit in all mass region
- using Υ $1S$: $2S$: $3S$ ratio from CDF (Phys. Rev. Lett. **88** 161802 (2002))

  $N_{\Upsilon(1S,2S,3S)} = 64 \pm 16$

  (x0.73 to get $1S$)
- Sidebands background normalisation

  The data events and BH fraction in (9.33-9.66) GeV mass range:
  - $N_{data} = 92 \pm 9$
  - $N_{BH} = 52 \pm 1$

The Elastic t-slope Estimation: Fit to the $dN/d|t|$ distribution



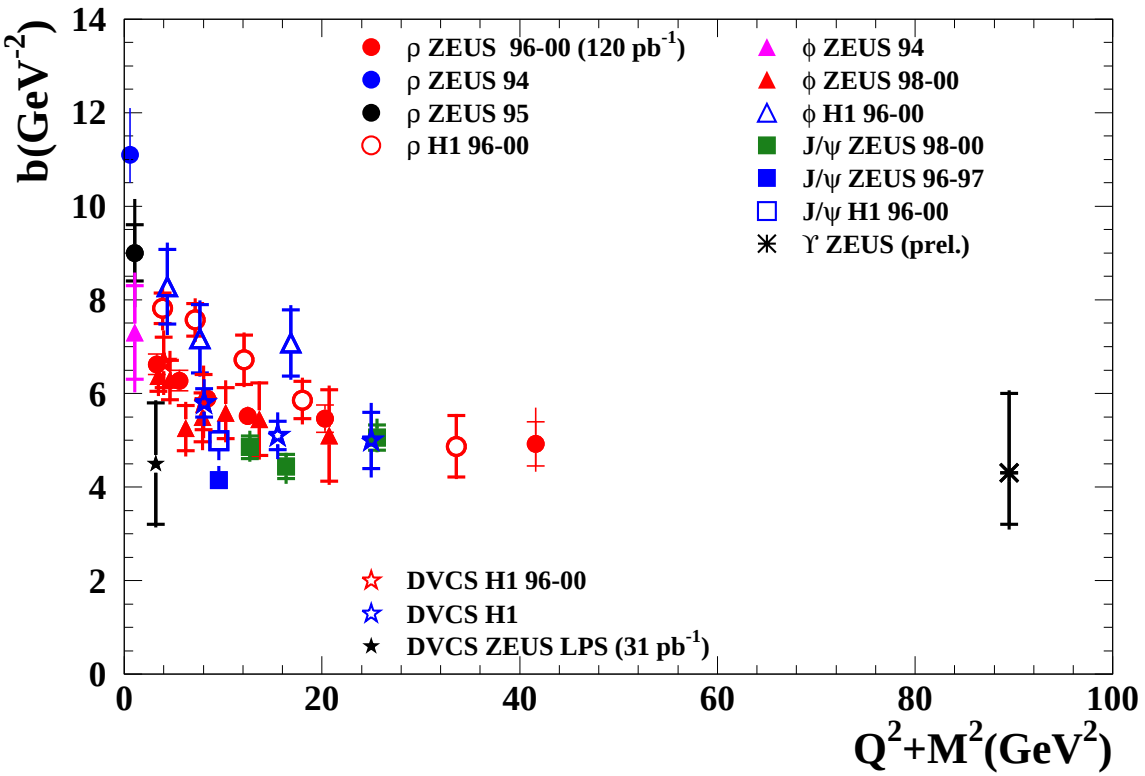
$dN/d|t|$ distribution
for events in the mass range (9.33-9.66) GeV:

- $\Upsilon(1S)$ signal and BH background normalisation fixed from mass fit
- $\Upsilon(1S)$ signal splited between elastic and pdiss (75:25) (syst.)
- The $\Upsilon(1S)$ slope b_{pdiss} = 0.65 (syst.)
- BH shape is treated as well known (syst.)
- binned maximum log-likelihood fit to extract the elastic b slope parameter

The $\Upsilon(1S)$ elastic t-slope b Value

ZEUS Preliminary:

$\Upsilon(1S)$ elastic PHP t-slope: $b = 4.3^{+1.7}_{-1.1}\ ^{+0.5}_{-0.5}$ (GeV^{-2})



measurement of the t-slope b for $\Upsilon(1S)$ meson
doubles the scale $Q^2+M_V^2$ explored by previous studies

Summary and Conclusions

- $\Upsilon(1S)$ elastic PHP t-slope: $b = 4.3^{+1.7\ +0.5}_{-1.1\ -0.5}$ (GeV^{-2})
- measurement was performed at the highest scale $Q^2 + M_V^2 = 89.5$ GeV^2 achieved for the vector meson
- value of the elastic t-slope parameter b is in agreement with the pQCD predictions and with the expectations implied by the proton radius

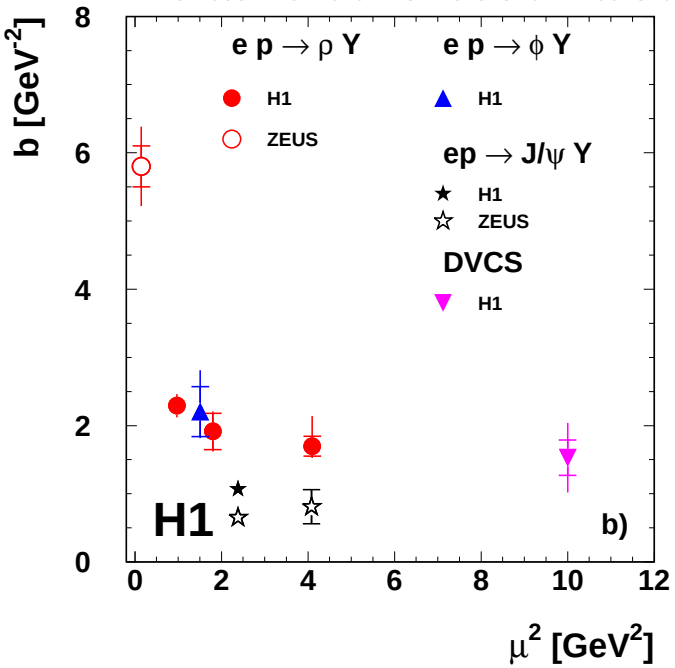
Thank You For Your Attention

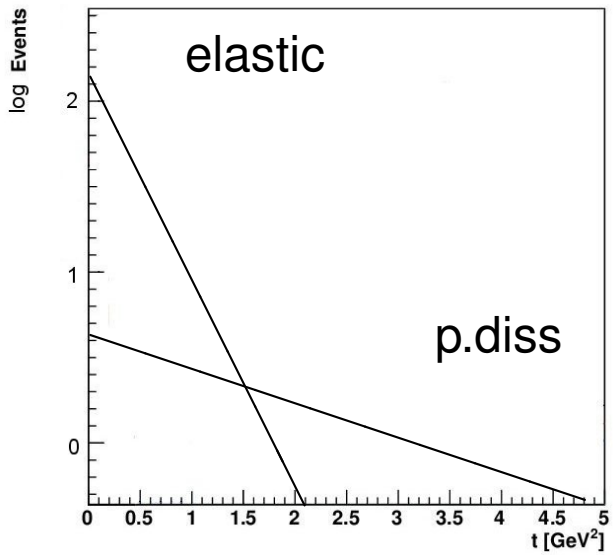
BACKUP PLOTS FOLLOWS...

Υ Proton Dissociative t-slope: b_{pdiss}

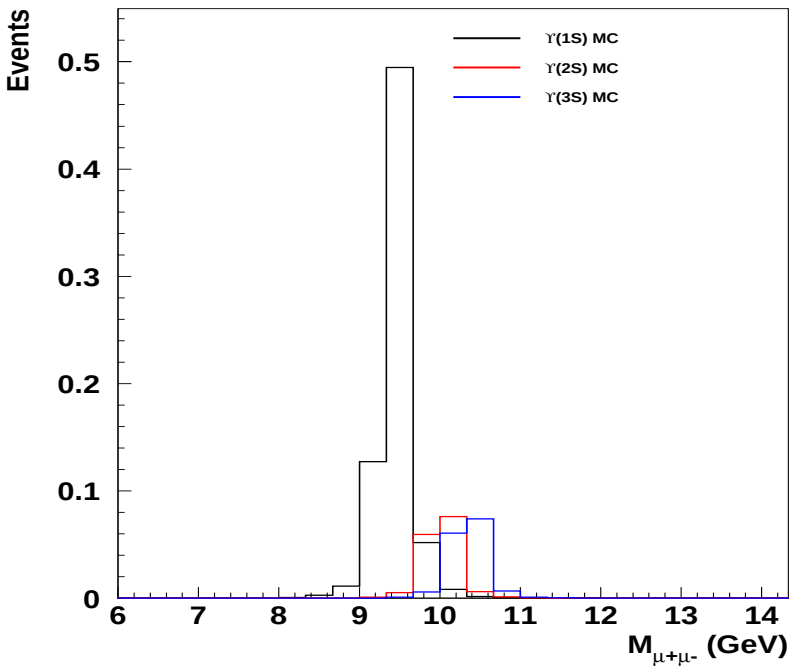
$\frac{d\sigma}{d|t|} \sim e^{-b|t|}$, has two components:

- The "elastic" and "p.diss" events have different t-slopes, b:
- elastic: $b_{el} \approx 4 \div 12$ GeV^{-2}, depends on M_V^2, Q^2
- p.diss: $b_{pdiss} \approx 0.5 \div 2$ GeV^{-2}, does not depend on M_V^2, Q^2
- p.diss: b_{pdiss} similar for all heavy Vector Mesons, we assume $b_{pdiss} \approx 0.65$ GeV^{-2} as for ZEUS J/Ψ analysis (Eur. Phys. J. **C 24**, 345)
- relative contribution also does not depend on event kinematics.





Υ Mass Resolution (from MC Study)

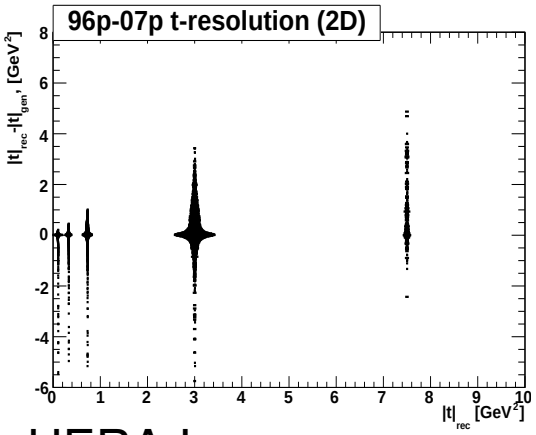


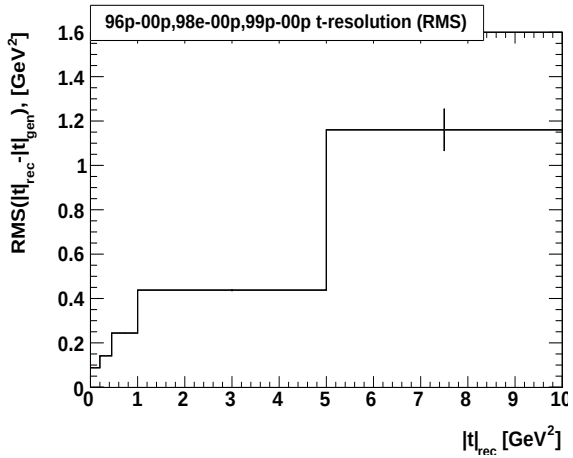
$\Upsilon(3S)$ normalised to $\Upsilon(2S)$ for better visualisation

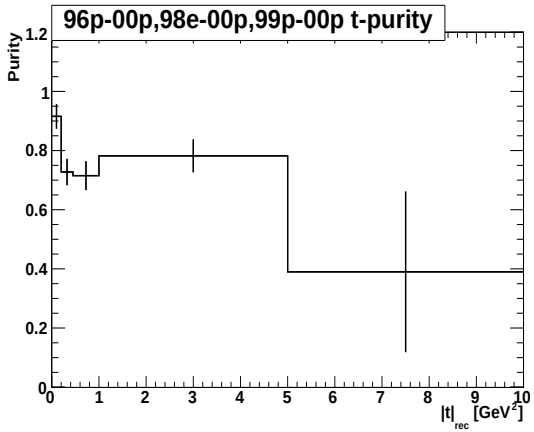
The $\Upsilon(1S)$, $\Upsilon(2S)$, $\Upsilon(3)$ states:

- ratio 1S:2S:3S = 0.73 : 0.19 : 0.08 (CDF-2002: Phys. Rev. Lett. **88** 161802)
- $M_{\Upsilon(1S)}$ = 9.46 GeV, mass peak width $\sim$ 200 MeV
- Mass window cut at 9.33 to 9.66 was chosen to improve the track resolution (implies t-resolution), and minimise contribution of the background (lower side) and higher excitation states (upper side)
- The mass range (9.33-9.66) GeV contains: 71% (1S), 3.4% (2S), 0.7% (3S). (relative: 1% (2S), 0.2% (3S))

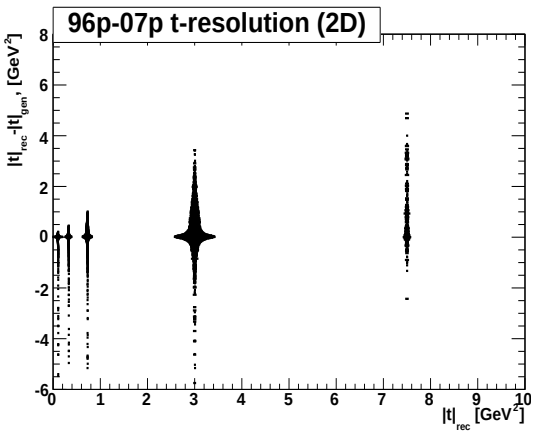
$\Upsilon(1S)$: t-resolution and purity in $|t|$ bins

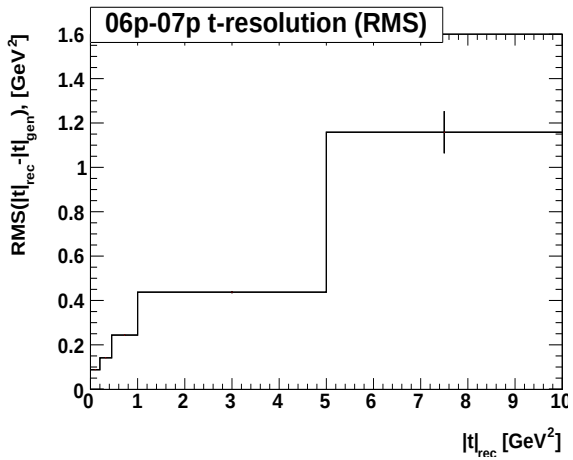


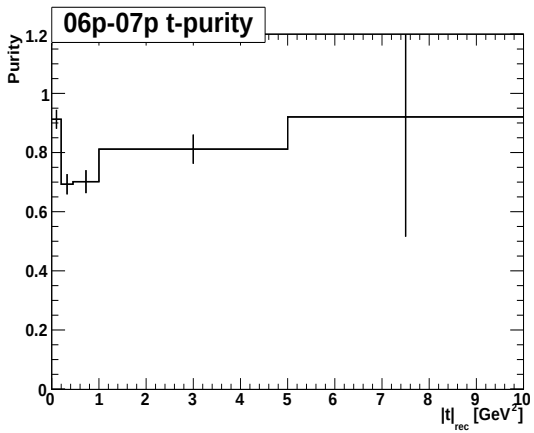




HERA I



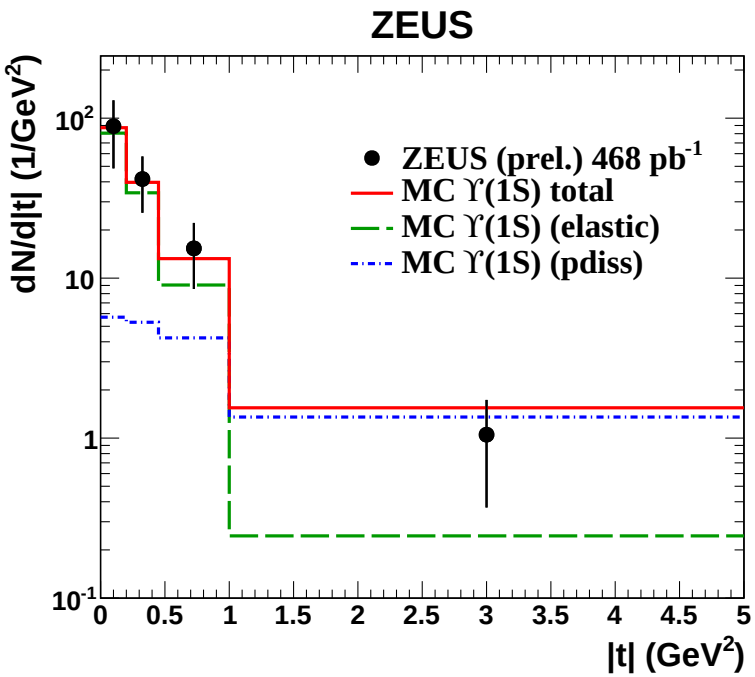




HERA II

t-bin width selected to be $\sim$ x2 of the RMS(t_{rec}-t_{gen}) in the bin

The t-slope Estimation: BG Subtracted Plot



$$-2\ln\lambda(\boldsymbol{\theta}) = 2\sum_{i=1}^{N}\left[\nu_i(\boldsymbol{\theta}) - n_i + n_i \ln\frac{n_i}{\nu_i(\boldsymbol{\theta})}\right]$$

$dN/d|t|$ distribution
for events in the mass range (9.33-9.66) GeV:

- data: 92 ($\pm$ 9) events
- BH: expect 52 ($\pm$ 1) events (syst.)
- the rest splits between $\Upsilon(1S)$: elastic and pdiss (75:25) (syst.)
- BH shape is treated as well known (syst.)
- The $\Upsilon(1S)$ b_{pdiss} = 0.65 (syst.)
- The $\Upsilon(1S)$ b_{el} is iteratively assigned a value in the range from 2.0 to 7.0 GeV^2 with an incremental step 0.1 GeV^2 (by re-weighting MC, using *generator level* b_{el} value)
- for each iteration a likelihood function was estimated according to the PDG formula.
- Similar LL calculation encoded in TFractionFitter takes into account also statistical errors in MC.

Systematics

- Υ f_{pdiss}: proton dissociative production fraction (contributes at higher t, $\approx 1 < t < 10$ GeV ^{2})
  - (25 $\pm$ 5) % $\rightarrow$ +0.30, -0.25
- Υ proton dissociative t-slope value b_{pdiss}
  - $0.65\ ^{+0.70}_{-0.10} \rightarrow\ ^{-0.4}_{+0.1}$
- BH f_{pdiss}: (variation of QEL/EL BH fraction)
  - variation within it's uncertainty of 3% (data.to.MC t-distribution comparison)
  - less then $\pm$ 0.30
- BH relative contribution (in the 9.33-9.66 GeV mass range)
  - (55.7 $\pm$ 1.2) % $\rightarrow$ +0.15, -0.10 (fraction of BH/DATA)