

Measurement of the cross-section ratio $\sigma_{\psi(2S)}/\sigma_{J/\psi(1S)}$ in exclusive photoproduction at HERA

Grzegorz Grzelak
(on behalf of the ZEUS collaboration)

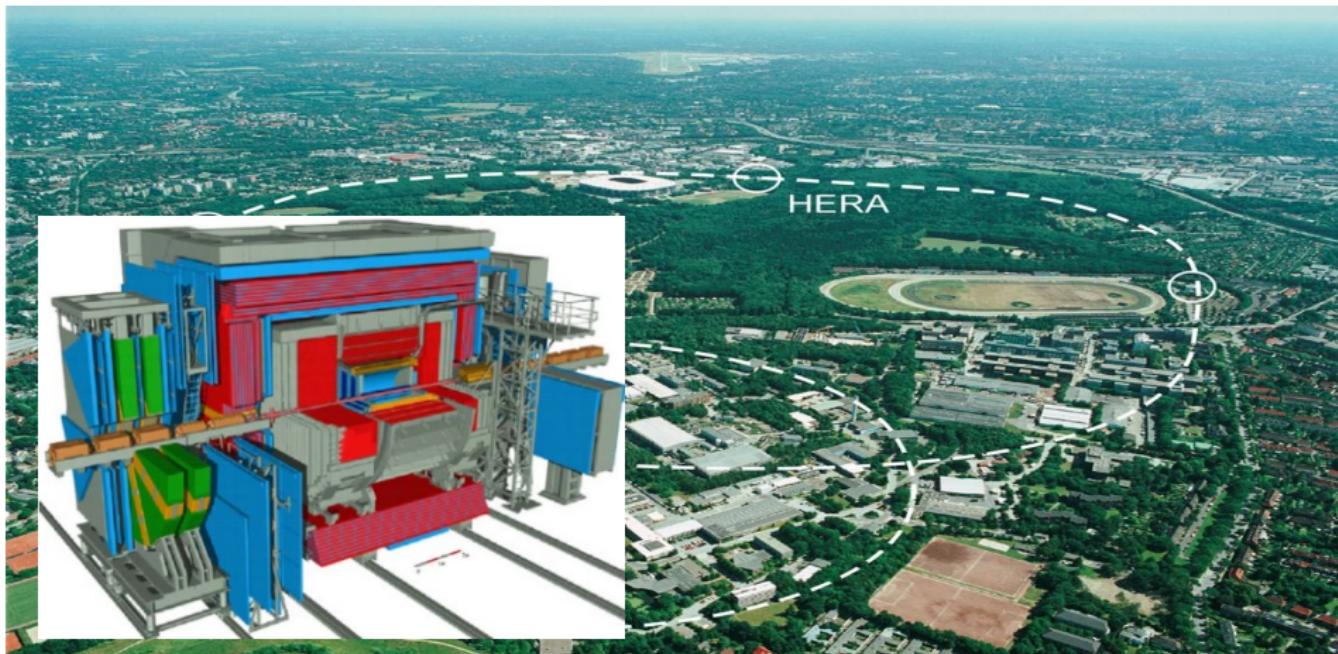
Faculty of Physics
University of Warsaw



13th International Workshop on Multiple Partonic Interactions at the LHC 2022
IFT, Universidad Autonoma de Madrid/CSIC, Madrid, Spain, November 14 – 18 (2022)

HERA and ZEUS: 1992 – 2007, DESY, Hamburg

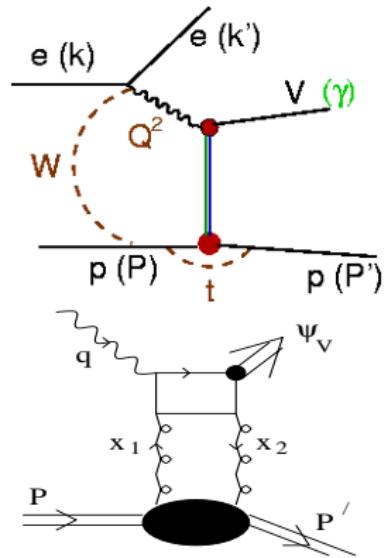
HERA: world's first and only $e^\pm p$ collider, $E_e = 27.5$ GeV, $E_p = 920$ GeV ($\sqrt{s} = 318$ GeV)



ZEUS: multipurpose, hermetic detector (MVD, CTD, CAL, F/B/RMUON, BAC, ...)

Total luminosity: $\int \mathcal{L} \sim 500 \text{ pb}^{-1}$ collected during HERA I + II running periods

Production of Vector Mesons in Exclusive Diffraction in ep Scattering



Exclusive process: proton stays intact
Proton dissociation also possible →
background

pQCD: M_V^2 and Q^2 - set the scale at which the W and $|t|$ are probed
Process sensitive to the **gluon density** in the proton

Kinematics: $M_V^2, Q^2, W, |t|$

M_V^2 - vector meson mass squared

$Q^2 (= -q^2 = -(k - k')^2)$ - the photon virtuality
(emitted by the incoming electron):

- $Q^2 \approx 0$ GeV² PHP (*Photoproduction*)
- larger Q^2 for DIS (*Deep Inelastic Scattering*)

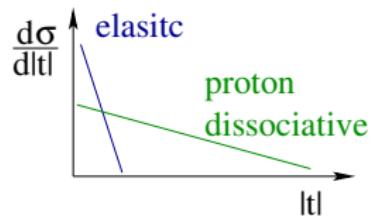
$W = (q + P)^2$ - invariant mass of the γp system

$$W \approx \sqrt{2E_P(E - p_z)_V}$$

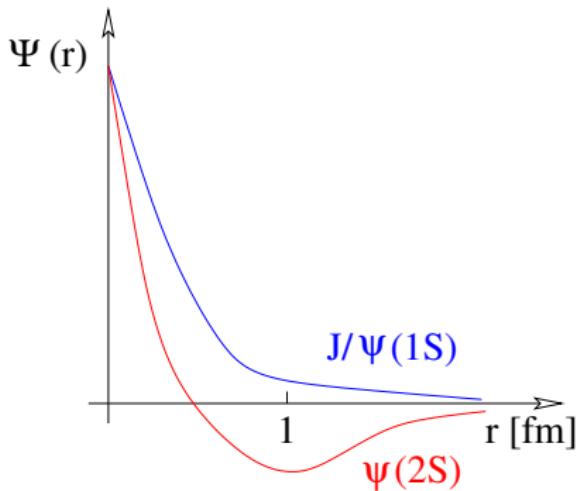
$|t|$ - 4-momentum transfer at the proton vertex

$$t = (P - P')^2$$

$$t \approx -p_{T,V}^2$$



Cross section ratio $\psi(2S)/J/\psi(1S)$

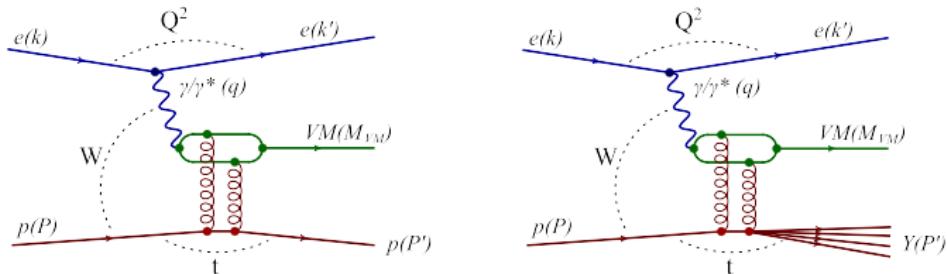


$$\text{Ratio } R = \frac{\sigma_{\gamma p \rightarrow \psi(2S)p}}{\sigma_{\gamma p \rightarrow J/\psi(1S)p}}$$

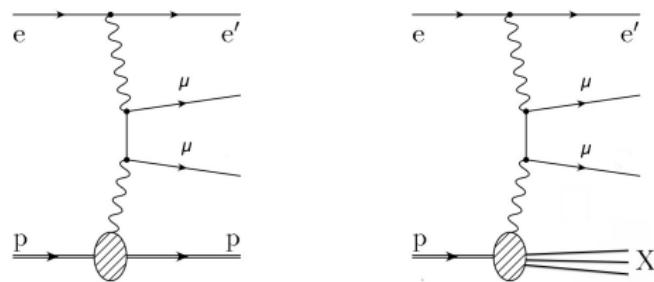
- sensitive to radial wave function of charmonium
- provides insight into the dynamics of the hard process
- from experimental point of view: some important systematics cancels out

- $J/\psi(1S)$ and $\psi(2S)$ have the same quark composition but distinctive wave functions
- $\psi(2S)$ has a node at ≈ 0.4 fm
- $\langle r_{\psi(2S)}^2 \rangle \approx 2 \langle r_{J/\psi(1S)}^2 \rangle$
- pQCD models predict $R \sim 0.17$ in PHP and rise of R with Q^2 in DIS
- $\psi(2S)$ cross section is expected to be suppressed w.r.t. the J/ψ production
- (Both Vector Mesons masses are much smaller than the γp center-of-mass energy)

- **Signal MC:** DIFFVM (VM production in ep scattering)

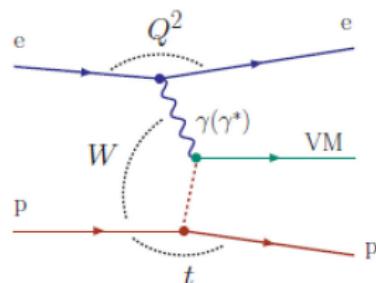
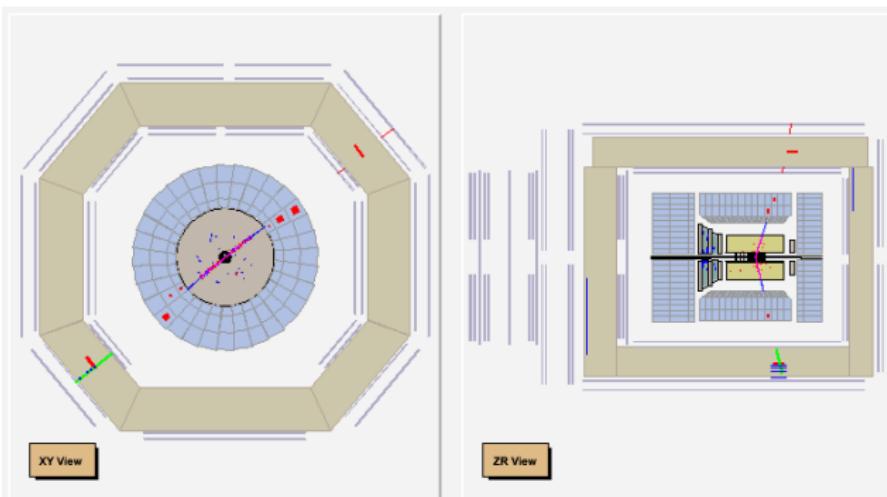


- **Background MC:** GRAPE (Bethe-Heitler continuum $\mu^+ \mu^-$)



- **HERA II DATA:** $\mathcal{L} = 373 \text{ pb}^{-1}$ (2003 - 2007)
- **Investigated decay channels:**
 - $\psi(2S) \rightarrow \mu^+ \mu^-$, $\psi(2S) \rightarrow J/\psi + \pi^+ \pi^-$, $J/\psi(1S) \rightarrow \mu^+ \mu^-$
- **exclusive (elastic) photoproduction sample**
- **kinematic range (analysis phase space):**
 - $30 < W < 180 \text{ GeV}$
 - $|t| < 1.0 \text{ GeV}^2$
 - $Q^2 < 1 \text{ GeV}^2$ (median $Q^2 \approx 3 \times 10^{-5} \text{ GeV}^2$)
- **differential measurement in 5 W and 5 $|t|$ bins**

Example of Final State Topology for $ep \rightarrow J/\psi p$, $J/\psi \rightarrow \mu^+ \mu^-$



Exclusive process, reaction mediated by exchange of colorless object; proton stays intact.

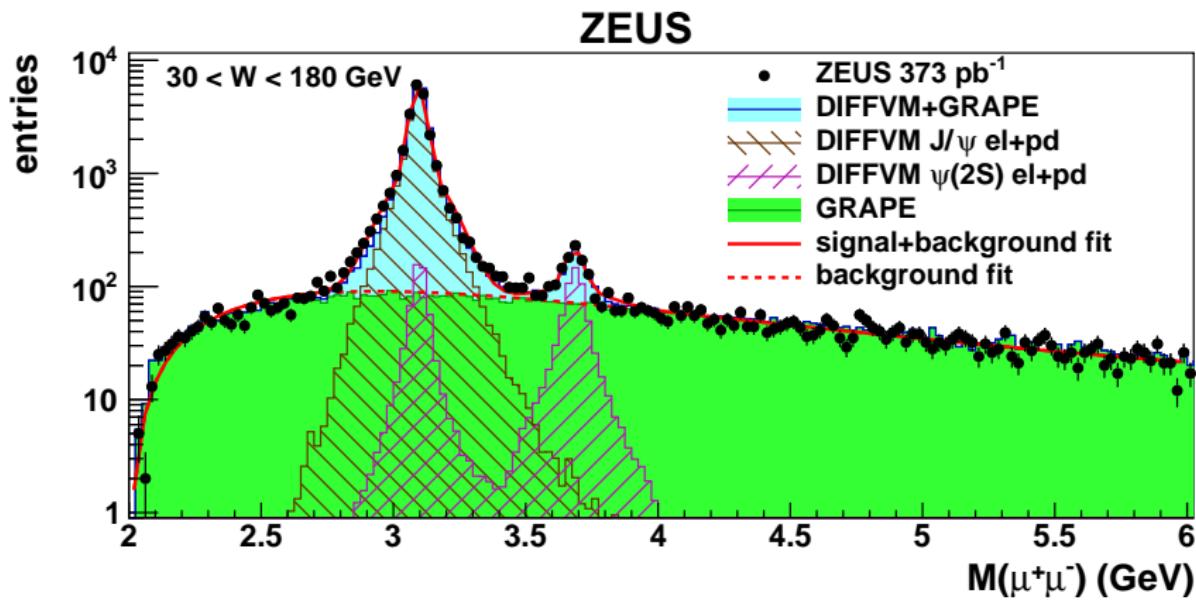
J/ψ and $\psi(2S)$ are detected in the 2- or 4-prong final states ($\mu^+ \mu^-$ or $\mu^+ \mu^- \pi^+ \pi^-$) very clean final state topology:

Photoproduction ($Q^2 < 1 \text{ GeV}^2$): two or four charged particles and nothing else
⇒ experimental challenge: triggering on soft muons

(Electroproduction ($Q^2 > 1 \text{ GeV}^2$): scattered electron also visible in the detector)

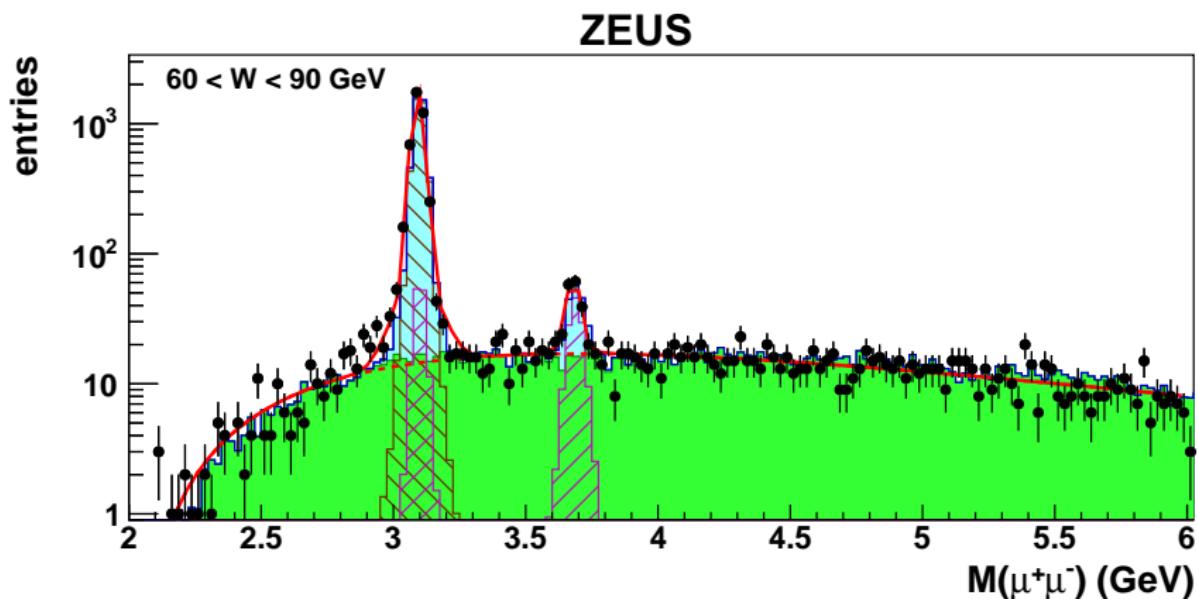
NOTE THE OPENING ANGLE OF THE DECAY PRODUCTS

- **Signal Extraction, Mass spectra**

$M(\mu^+\mu^-)$ 

- full phase space: $30 < W < 180 \text{ GeV}, |t| < 1.0 \text{ GeV}^2$
- events yield: $\sim 23\,000 J/\psi$ and $\sim 700 \psi(2S)$
- resonant background under J/ψ peak

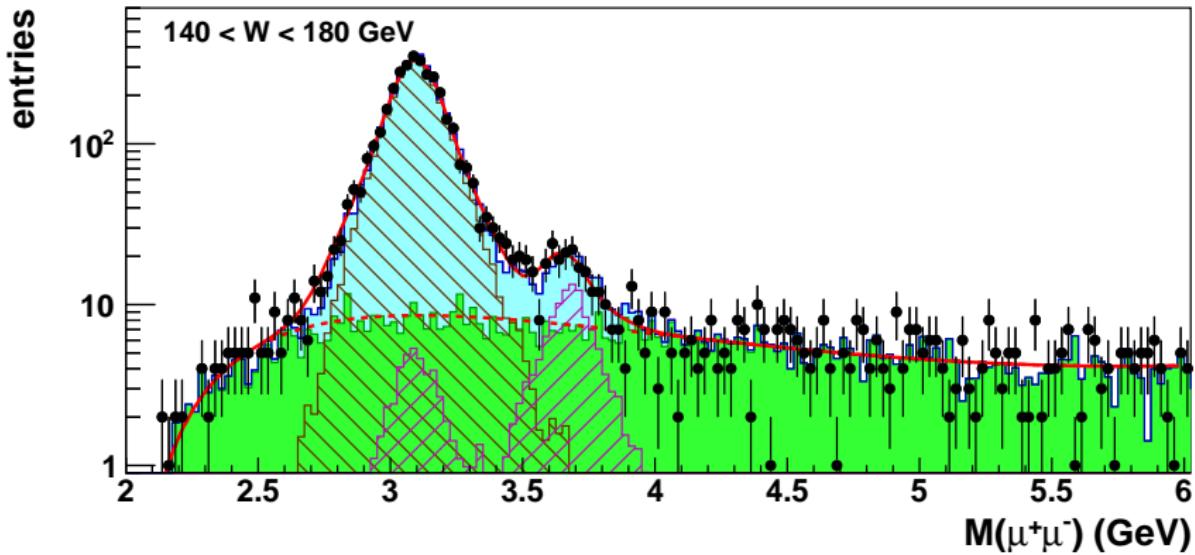
$M(\mu^+ \mu^-)$



- **W2 bin:** $60 < W < 90 \text{ GeV}$, $|t| < 1.0 \text{ GeV}^2$
 - central rapidity region, long tracks, mass resolution: $\sigma_M(\mu\mu) \sim 22 \text{ MeV}$

$M(\mu^+\mu^-)$

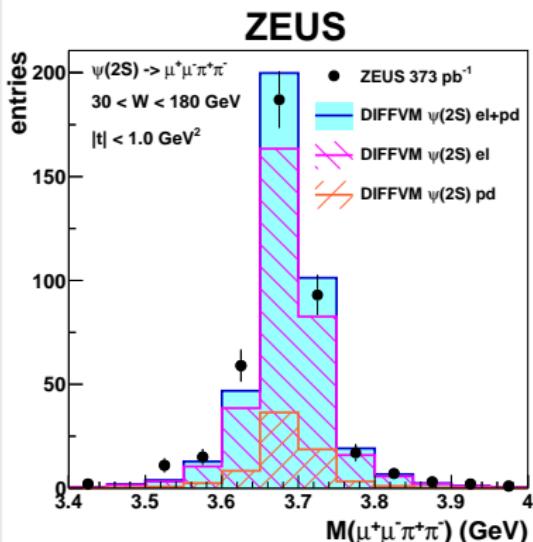
ZEUS



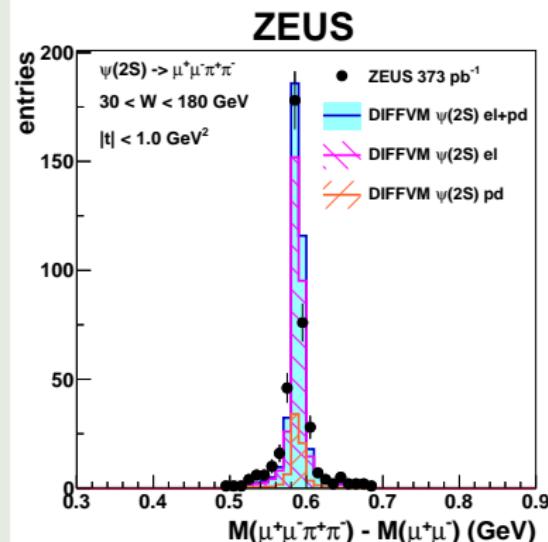
- **W5 bin:** $140 < W < 180 \text{ GeV}, |t| < 1.0 \text{ GeV}^2$
- high W , backward short tracks, mass resolution: $\sigma_M(\mu\mu) \sim 73 \text{ MeV}$

4-prongs: mass spectra

$$M(\mu^+\mu^-\pi^+\pi^-)$$



$$M(\mu^+\mu^-\pi^+\pi^-) - M(\mu^+\mu^-)$$

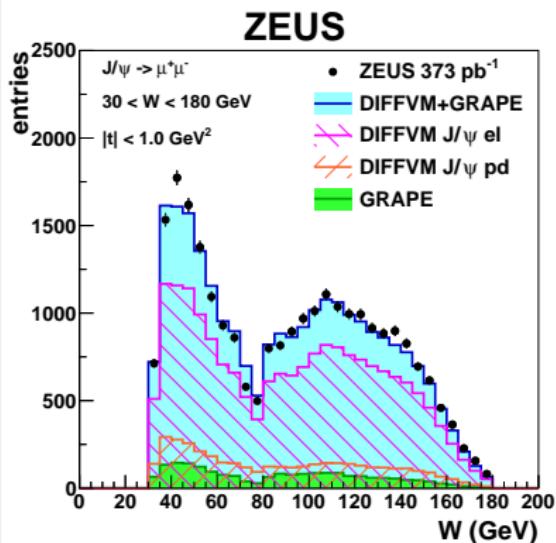


- events yield: $\sim 400 \psi(2S)$
- better resolution on mass difference \rightarrow cascade decay of $\psi(2S)$
- proton dissociative fraction: $f_{p.diss} = 0.16 \pm 0.01$ from t -spectra fit

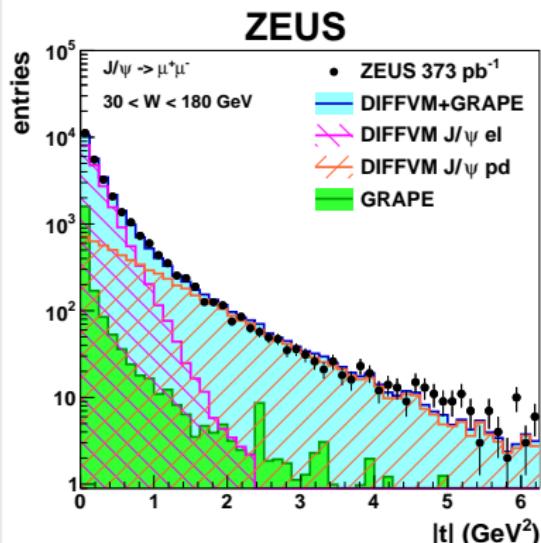
- **W and $|t|$ distributions: 2-prongs**

2-prongs: W and $|t|$ distributions: J/ψ mass window

W : $2.8 < M(\mu^+ \mu^-) < 3.4$ GeV



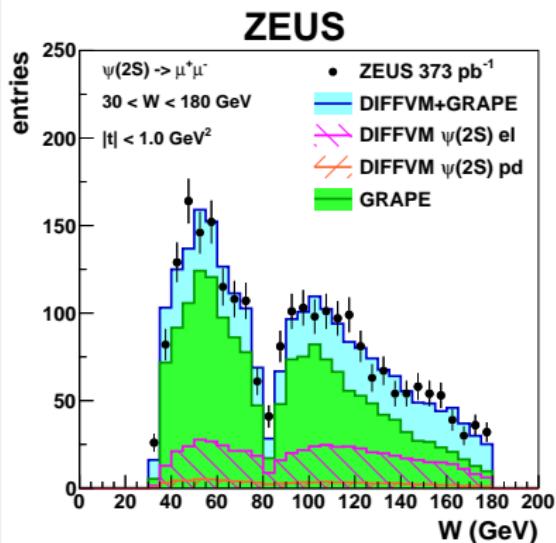
| t |: $2.8 < M(\mu^+ \mu^-) < 3.4$ GeV



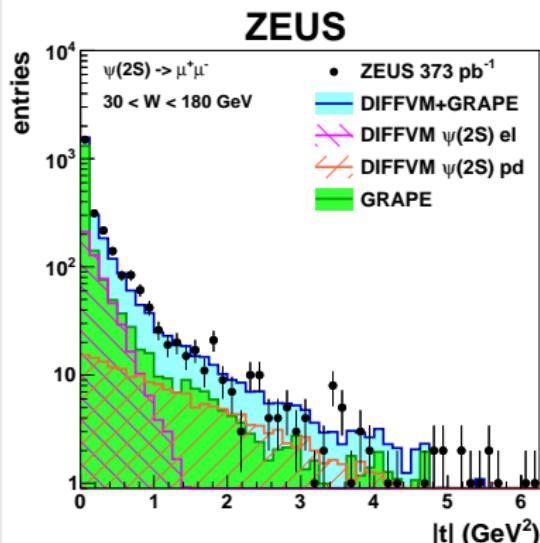
- dip in W distribution due to the anti-COSMIC cut: $\cos(\mu^+, \mu^-) < -0.985$
 - proton dissociation dominates for $|t| > 1.0 \text{ GeV}^2$
 - proton dissociative fraction: $f_{p,diss} = 0.17 \pm 0.01$ ($|t| < 1.0 \text{ GeV}^2$) from t -spectra fit

2-prongs: W and $|t|$ distributions: $\psi(2S)$ mass window

W : $3.4 < M(\mu^+ \mu^-) < 4.0$ GeV



| t |: $3.4 < M(\mu^+ \mu^-) < 4.0$ GeV



- dip in W distribution due to the anti-COSMIC cut: $\cos(\mu^+, \mu^-) < -0.985$
 - proton dissociation dominates for $|t| > 1.0 \text{ GeV}^2$
 - channel dominated by Bethe-Heitler continuum $\mu^+ \mu^-$ background

- Cross section ratio

Cross section ratio $R = \frac{\sigma(\psi(2S))}{\sigma(J/\psi(1S))}$, full kinematic range

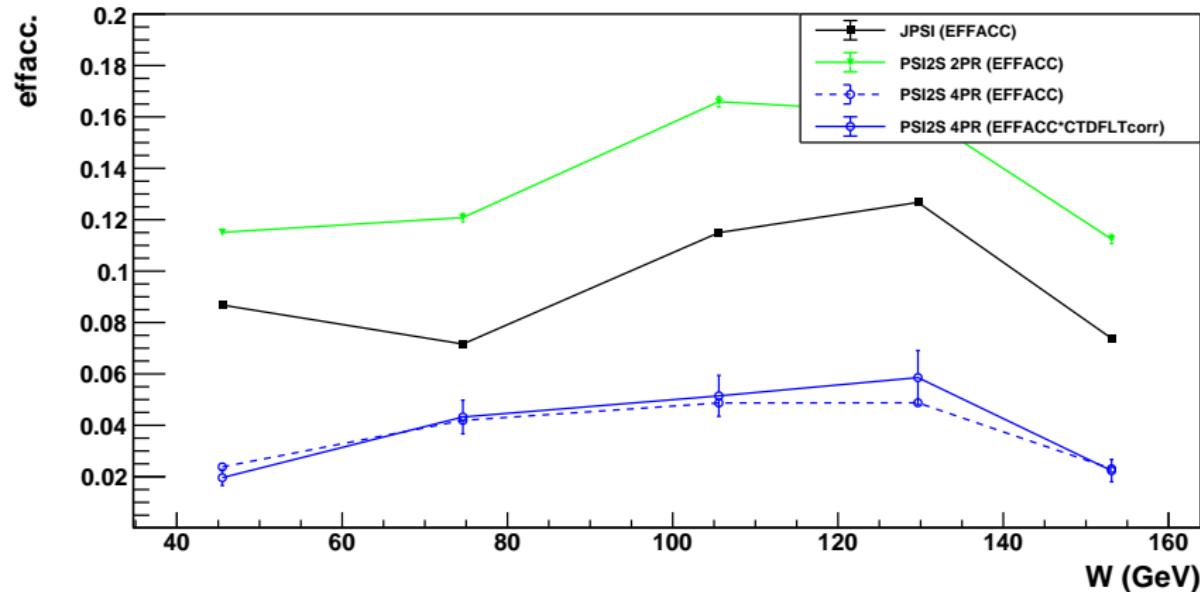
$30 < W < 180$ GeV, $|t| < 1.0$ GeV 2 , $Q^2 < 1.0$ GeV 2

$\psi(2S)$ decay mode	$R = \frac{\sigma(\psi(2S))}{\sigma(J/\psi(1S))}$
$\mu^+ \mu^-$	0.154 ± 0.012
$J/\psi(\rightarrow \mu^+ \mu^-) \pi^+ \pi^-$	0.125 ± 0.019
combined	$0.146 \pm 0.010^{+0.016}_{-0.020}$

- $R_{J/\psi \pi \pi} = \frac{N_{\psi(2S)}}{N_{J/\psi(1S)}} \cdot \frac{Acc_{J/\psi(1S) \rightarrow \mu^+ \mu^-}}{Acc_{\psi(2S) \rightarrow J/\psi \pi^+ \pi^-}} \cdot \frac{1}{BR_{\psi(2S) \rightarrow J/\psi \pi^+ \pi^-}} \cdot \frac{1 - f_{pdiss}^{\psi(2S)}}{1 - f_{pdiss}^{J/\psi(1S)}}$
- $R_{\mu\mu} = \frac{N_{\psi(2S)}}{N_{J/\psi(1S)}} \cdot \frac{Acc_{J/\psi(1S) \rightarrow \mu^+ \mu^-}}{Acc_{\psi(2S) \rightarrow \mu^+ \mu^-}} \cdot \frac{BR_{J/\psi(1S) \rightarrow \mu^+ \mu^-}}{BR_{\psi(2S) \rightarrow \mu^+ \mu^-}} \cdot \frac{1 - f_{pdiss}^{\psi(2S)}}{1 - f_{pdiss}^{J/\psi(1S)}}$
- $Acc_i = \frac{N_i^{reco}}{N_i^{true}}$, $f_{p.diss}^i$ - fraction of proton dissociative events
- $BR(\psi(2S) \rightarrow J/\psi \pi^+ \pi^-) = (34.68 \pm 0.3)\%$, $BR(\psi(2S) \rightarrow \mu^+ \mu^-) = (0.80 \pm 0.06)\%$,
 $BR(J/\psi \rightarrow \mu^+ \mu^-) = (5.961 \pm 0.033)\%$, $BR(\psi(2S) \rightarrow \mu^+ \mu^- \pi^+ \pi^-) = (2.07 \pm 0.02)\%$ (PDG 2020)
- both channels have similar precision and provide consistent results

Acceptance*efficiency in W bins: elastic

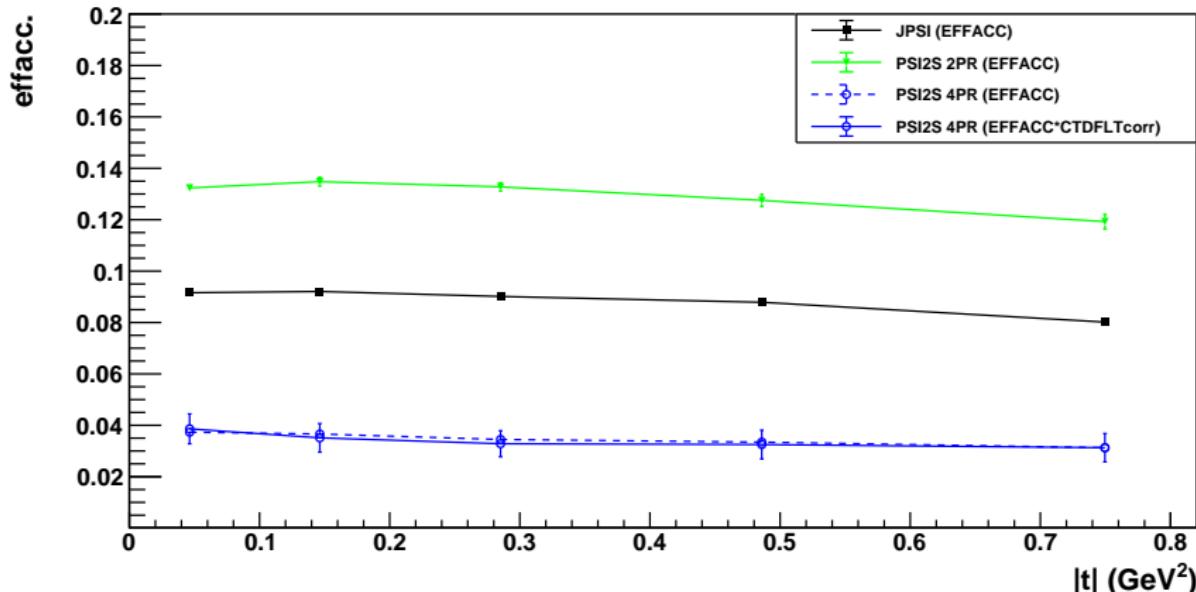
EFFACC (el) of JPSI, PSI2S-2PR, PSI2S-4PR vs. W



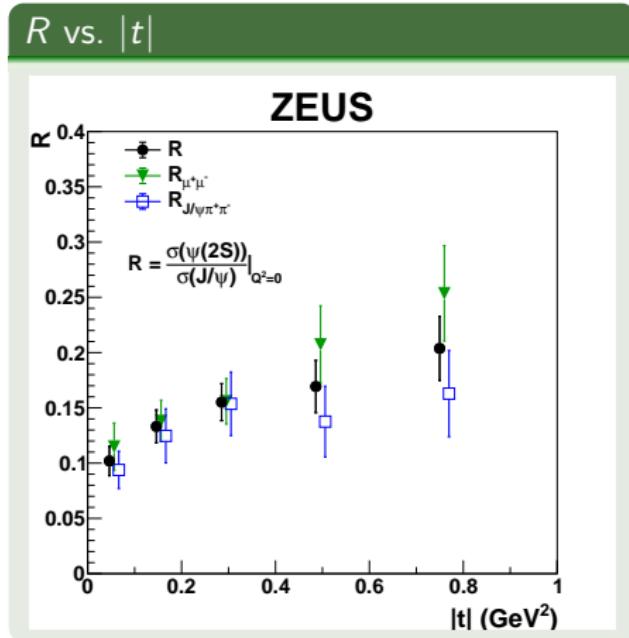
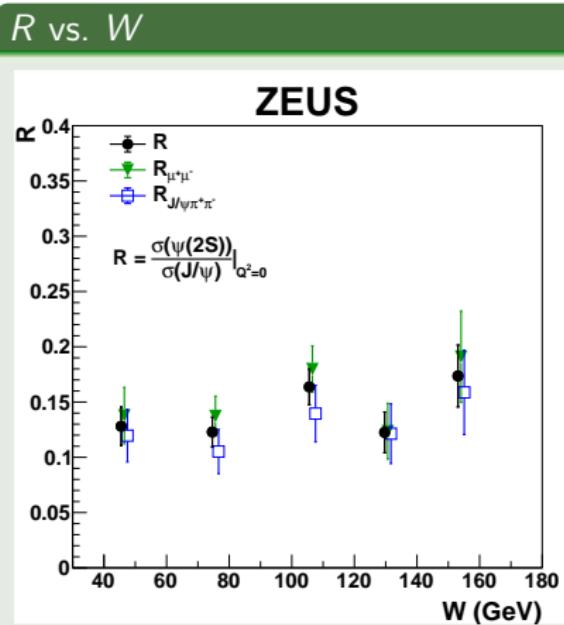
- JPSI, PSI2S 2- and 4-prong ($2 \div 16\%$)
- Higher di-muon acceptance for higher mass state (PSI2S)
- different angular coverage for final state muons
- second W bin (W_2) is the “dip” for di-muon acceptance

Acceptance*efficiency in $|t|$ bins: elastic

EFFACC (el) of JPSI, PSI2S-2PR, PSI2S-4PR vs. $|t|$



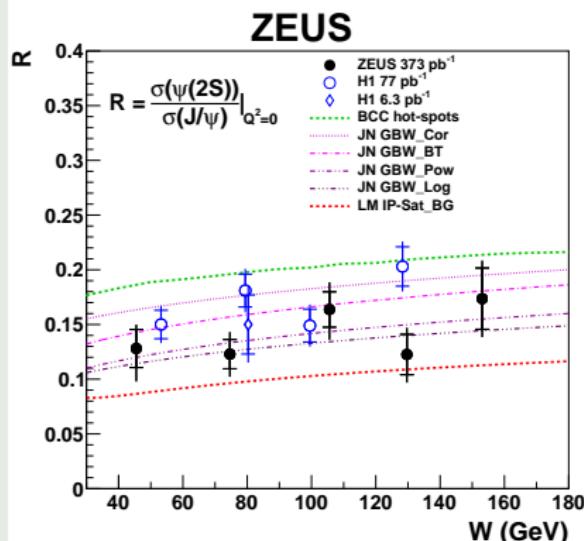
- JPSI, PSI2S 2- and 4-prong (**4 ÷ 12%**)
 - Higher di-muon acceptance for higher mass state (**PSI2S**)
 - flat in $|t|$ (no angular correlations to $|t|$)
 - dashed line after CTD FLT corrections



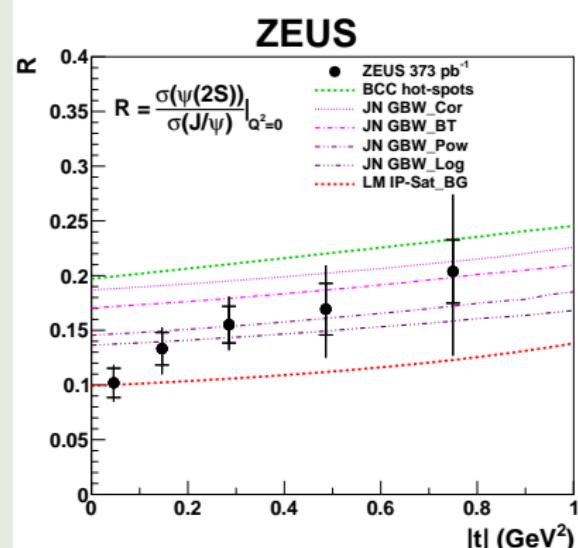
- $R_{\mu\mu}$ (2-prongs channel), $R_{J/\psi\pi\pi}$ (4-prongs channel) and combined R (full dots)
 - statistical errors only
 - **good agreement between two channels**

cross section ratio $R = \sigma_{\psi(2S)}/\sigma_{J/\psi(1S)}$: Final Results

R vs. W



R vs. $|t|$

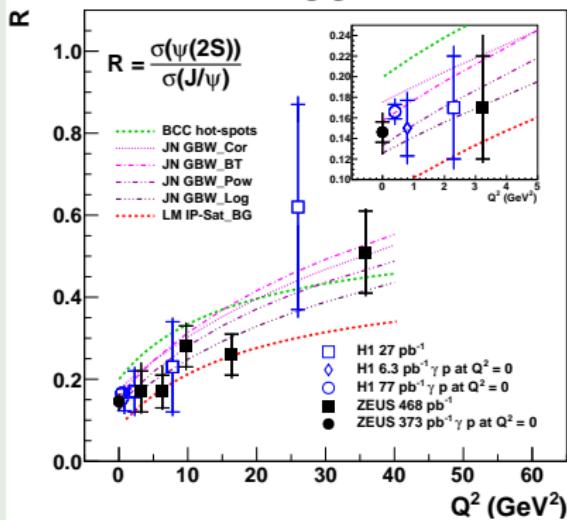


- for R vs. W ZEUS (full dots) and H1 (open markers) results are compared
- no W dependence observed, moderate increase with $|t|$**
- good agreement between data and theoretical models (see next page)
- errors at high- $|t|$ points dominated by systematics (\rightarrow proton dissociative fraction)

cross section ratio $R = \sigma_{\psi(2S)}/\sigma_{J/\psi(1S)}$: Final Results

R vs. Q^2

ZEUS



theoretical models:

- Bendova, Cepila and Contreras (BCC hot-spots):
 - Phys. Rev. D 99, 034025 (2019).
- Jan Nemchik et al. (JN):
 - Eur. Phys. J. C 79, 154 (2019).
 - Eur. Phys. J. C 79, 495 (2019).
 - Phys. Rev. D 103, 094027 (2021).
- Lappi and Mäntysaari (LM IP-Sat):
 - Phys. Rev. C 83, 065202 (2011).
 - Phys. Rev. D 87, 034002 (2013).
 - PoS (DIS2014), 069 (2014).

- ZEUS (full dot) and H1 (open markers) photoproduction results plotted at $Q^2 \sim 0$
- DIS results are also presented vs. Q^2 : ZEUS (full squares) and H1 (open squares)
- good agreement between data and theoretical models (\rightarrow backup plots, page 33)
- **better precision of photoproduction points**

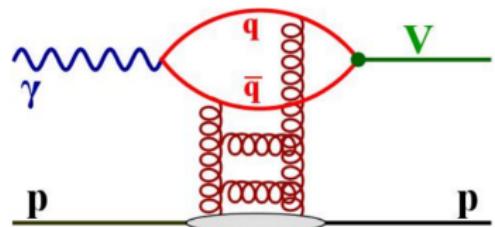
- **Cross section ratio $R = \frac{\sigma(\psi(2S))}{\sigma(J/\psi(1S))}$** in photoproduction using HERA II data was measured by ZEUS in the kinematic range: $30 < W < 180$ GeV, $|t| < 1.0$ GeV 2
- first ZEUS measurement of R in photoproduction (at $Q^2 = 0$):
$$R = 0.146 \pm 0.01 (\text{stat.})^{+0.016}_{-0.022} (\text{syst.})$$
- first HERA result for R vs. $|t|$ in photoproduction
- moderate rise of cross section ratio as a function of $|t|$
- no W dependence observed within experimental errors
- consistent results for 2- and 4-prongs decay channels
- comparable precision in both decay channels
- theoretical calculations of the ratio $\frac{\sigma(\psi(2S))}{\sigma(J/\psi(1S))}$ for exclusive vector-meson production has been compared to the experimental data
- → majority of the predictions are consistent with the data
- data start to exhibit constraining power

Thank You For Your Attention

BACKUP PLOTS

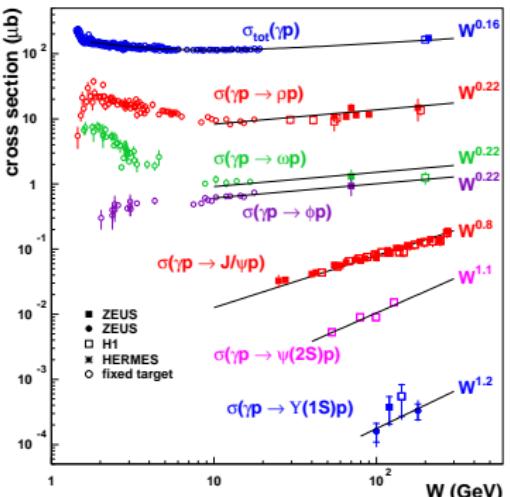
BACKUP PLOTS FOLLOWS...

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



- process driven by gluons
- $\sigma \propto [xg(x, \mu^2)]^2$
- $x = \mu^2/W^2$: high $W \rightarrow$ small x
- $\mu^2 \propto (Q^2 + M_V^2)$

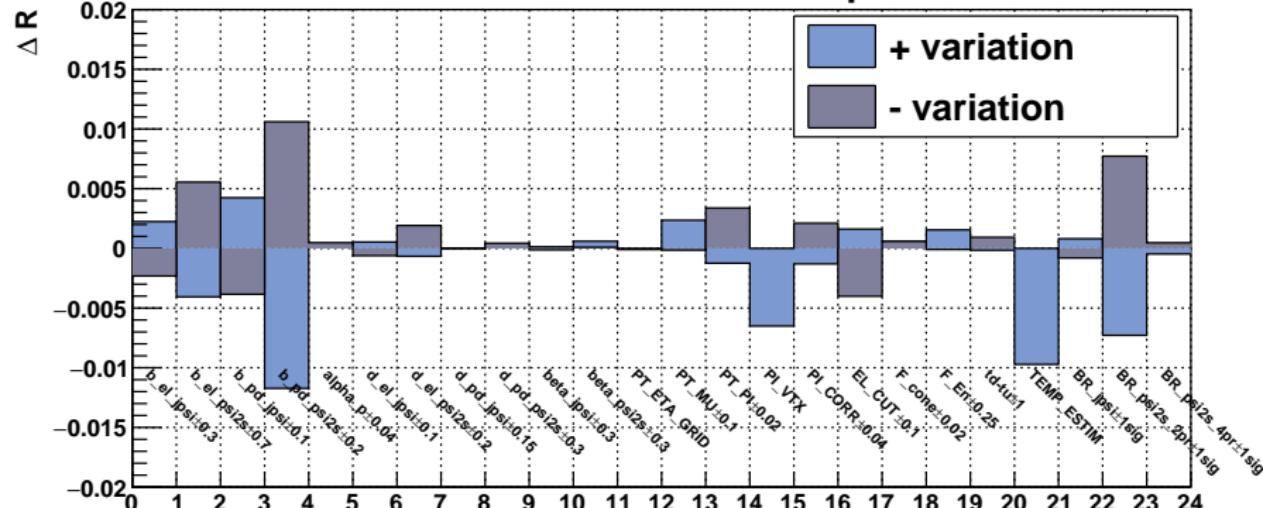
- total cross sections σ_{VM} for VM photoproduction spans over 6 orders of magnitude !
(for higher VM masses \rightarrow smaller transverse size of $q\bar{q} \rightarrow$ "color screening")
- σ_{VM} rises with γp c.m. energy W as W^δ ($x \sim 1/W^2$: high $W \rightarrow$ small x)
(for heavy VMs expected from the gluon behaviour in the proton \rightarrow probing small x)
- power δ rises with M_V^2 from "soft" ($\delta \approx 0.22$) to "hard" ($\delta \approx 1.2$) processes



- **Systematics**

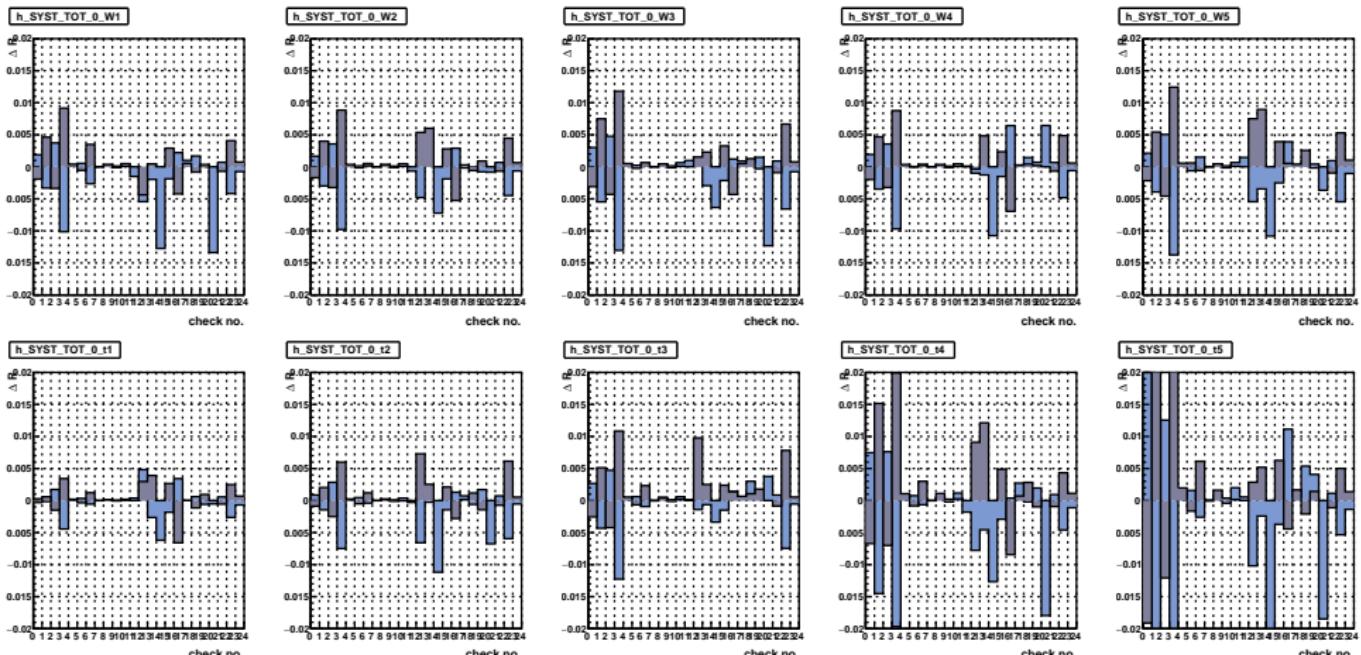
h_SYST_TOT_0

R GLOBAL: SYST error components



- biggest contributions from:
- b -slope variation of t -dependence (esp. for b_{pd} of $\psi(2S)$)
- event number estimator (MC templates fit instead of Gaussian fit)
- slow pions vertexing
- $BR(\psi(2S) \rightarrow \mu^+ \mu^-)$

R : components of SYST. error in W and $|t|$ bins

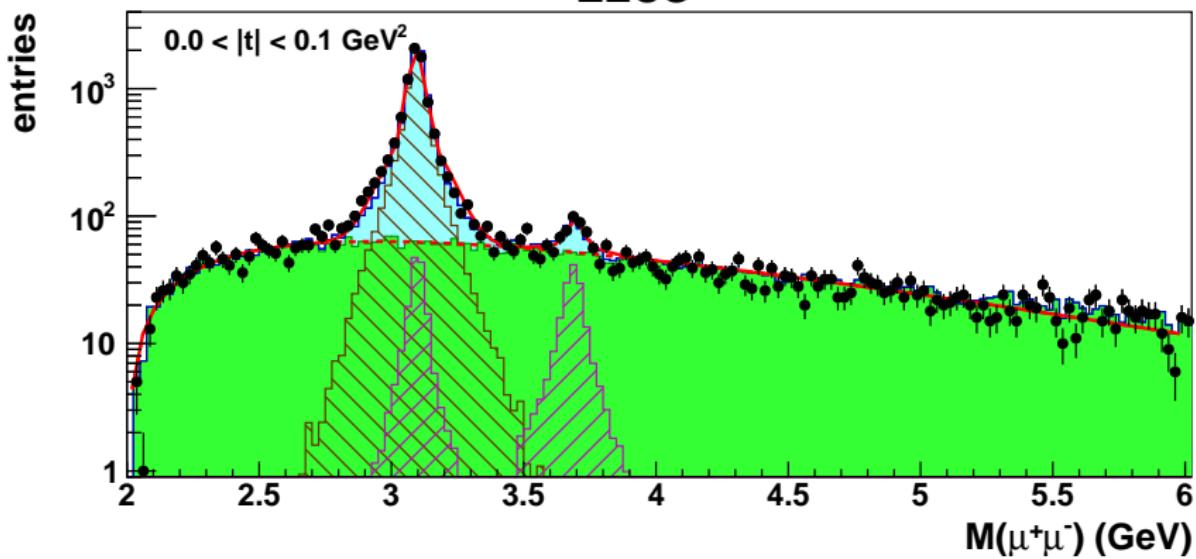


- upper row: contributions in 5 W bins
- bottom row: contributions in 5 $|t|$ bins
- bin order as on previous page

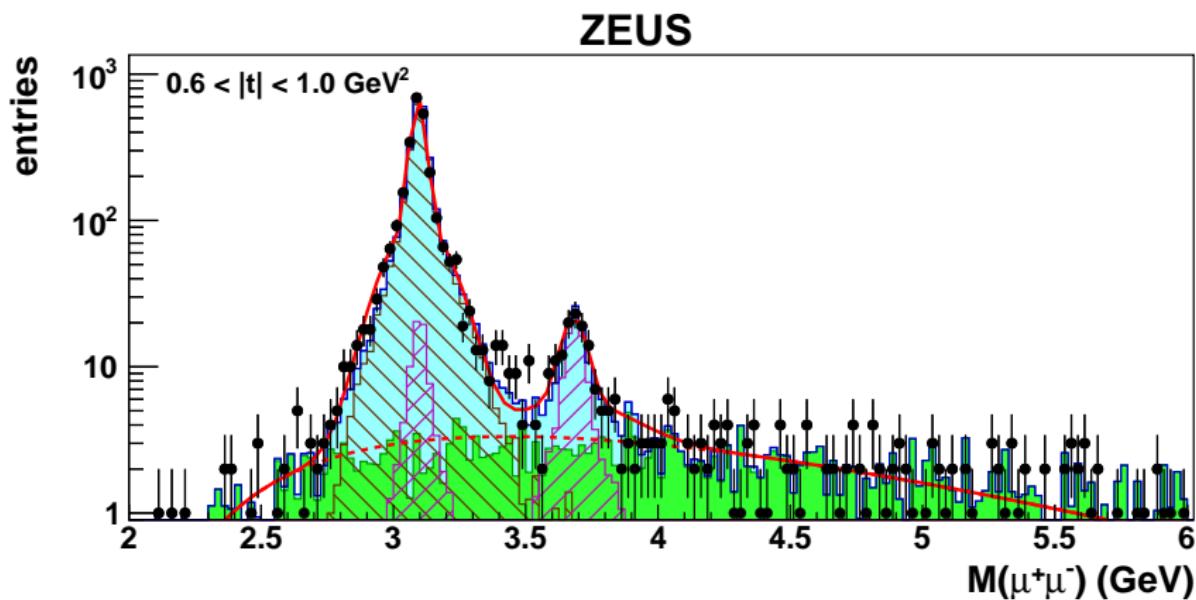
- dimuon mass spectra (backup)

$M(\mu^+\mu^-)$

ZEUS



- **t1 bin:** $30 < W < 180$ GeV, $|t| < 0.1$ GeV 2
- low $|t|$, dominated by Bethe-Heitler continuum $\mu^+\mu^-$ background

$M(\mu^+\mu^-)$ 

- **t5 bin:** $30 < W < 180 \text{ GeV}$, $0.6 < |t| < 1.0 \text{ GeV}^2$
- higher $|t|$, small Bethe-Heitler continuum $\mu^+\mu^-$ contribution
- **BUT: high contamination proton dissociative events** → t -spectra

- Theoretical Models

Theory predictions: models (1)

- **Bendova, Cepila and Contreras (BCC hot-spots) :**
- Phys. Rev. D **99**, 034025 (2019).
- model with hot spots randomly sampled in the transverse plane bound by the size of the proton
- The slope parameter b is 4.72 GeV^{-2} and it is fixed by the combined H1 and ZEUS data from 2013 for JPsi photoproduction t -distribution.
- the same b -slope for both JPsi and Psi2s

Theory predictions: models (2)

- **Jan Nemchik (JN) et al. :**
- Eur. Phys. J. C **79**, no.6, 495 (2019).
- Eur. Phys. J. C **79**, no.2, 154 (2019).
- calculations have been performed for various combinations of quarkonium wave functions:
 - **Cor** (Cornell potential)
 - **BT** (Buchmüller-Tye)
 - **Pow** (Power-law potential)
 - **Log** (Logarithmic potential)

and models for the dipole cross sections:

- BGBK, **GBW** ← used on the plots
- for each combinations calculations are performed with and w/o skewness in the gluon density
- the same b -slope parameters for both quarkonium states

Theory predictions: models (3)

- **Lappi and Mntysaari (LM IP-Sat) :**
- the BFKL evolution plus the IP-Sat model to predict vector-meson production in ep and electronion collisions in the dipole picture
- 2S parameters from arXiv:1406.2877 (PoS DIS2014 (2014) 069)
- 1S parameters from hep-ph/0606272 (Phys.Rev. **D74** (2006) 074016)
- Calculation described in (Phys.Rev. **C83** (2011) 065202)
- **IP-Sat** dipole from fit (Phys.Rev. **D87** (2013) no.3, 034002)
- Wave function: Boosted Gaussian (**BG**), $Q^2 = 0 \text{ GeV}^2$
- Skewedness and real part corrections included
- predictions of all models were calculated within the phase space of this analysis:
 - $30 < W < 180 \text{ GeV}$
 - $|t| < 1.0 \text{ GeV}^2$
 - $Q^2 \sim 0$ (photoproduction points)

- Signal extraction, cuts, control plots, ...

2-prongs: Signal extraction: fit parameterization

- Double Gaussian shape: $G(x)$ or $g(x) = N \cdot \Delta \cdot \frac{1}{\sqrt{2\pi}\sigma} \exp\left(-\frac{(x-m)^2}{2\sigma^2}\right)$
where: N – number of events, Δ – mass bin width,
 m – mean value, σ – RMS
- for J/ψ : $N_1 \cdot G_1(x) + N_2 \cdot G_2(x)$
- for ψ' : $N'_1 \cdot g_1(x) + N'_2 \cdot g_2(x)$
- introducing: $N = N_1 + N_2$, $N' = N'_1 + N'_2$, $R = \frac{N'}{N}$
- with additional constraints: $m_1 = m_2$, $m'_1 = m'_2$,
 $\frac{\sigma'_1}{\sigma_1} = \frac{\sigma'_2}{\sigma_2} = \alpha$, $\xi = \frac{N_1}{N} = \frac{N'_1}{N'}$ (**scaling of the mass resolution**)
- final formulae:

$$F(x) = N \cdot ((\xi \cdot G_1(x) + (1 - \xi) \cdot G_2(x)) + R \cdot (\xi \cdot g_1(x) + (1 - \xi) \cdot g_2(x))) + BG(x)$$

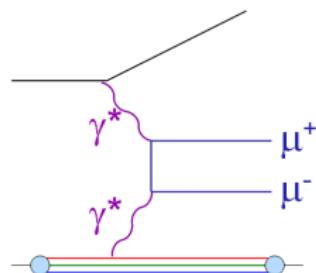
- background function: $BG(x) = A \cdot (x - B)^C \cdot \exp(-D(x - B) - E(x - B)^2)$
where A, B, C, D, E are fit parameters, B fixed ($= 2p_{t,min}^\mu$)

- Exclusive Muon Triggers (F/B/R/MUON or BAC)
- Tracking and Vertex
 - $N_{track} = 2$, oppositely charged tracks matched to the primary vertex ($\eta \in (-1.9, 1.9)$)
 - both tracks identified as a muon in CAL, at least one in F/B/RMUON or BAC
 - $p_T > 1.0$ GeV of each track
 - anti-COSMIC cuts (CAL timing, acolinearity: $\cos(\mu^+, \mu^-) < -0.985$)
- Elasticity/Exclusivity and Photoproduction cuts (on CAL Energy)
 - no scattered electron found in CAL
 - $E_{clu} < 0.5$ GeV for clusters not matched to muons (or pions)
(corresponds to an effective cut on $Q^2 < 1$ GeV 2)
 - $E(\theta < 0.12\text{rad}) < 1$ GeV
the sum of the energy in the FCAL cone around the beam-pipe;
to suppress proton-dissociative events, $ep \rightarrow e + VM + Y$
(corresponds to a requirement for $M_Y \lesssim 5$ GeV)
- Kinematic range (analysis phase space):
 - $30 < W < 180$ GeV
 - $|t| < 1.0$ GeV 2
 - $Q^2 < 1$ GeV 2 (median $Q^2 \approx 3 \times 10^{-5}$ GeV 2)

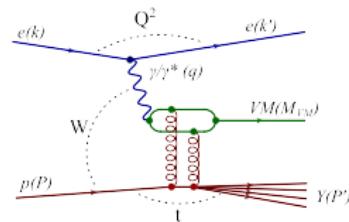
- (only differences w.r.t. the 2-prong channel)
- $N_{track} = 4$, (two oppositely charged pairs, sorted by p_T)
- highest momentum pair: muon candidates
lowest momentum pair: pion candidates
- no anti-COSMIC cuts
- transverse momentum of pion candidates: $p_T^\pi > 0.12$ GeV;
- $2.8 < M(\mu^+ \mu^-) < 3.4$ GeV (J/ψ window)
- $M(\mu^+ \mu^- \pi^+ \pi^-) - M(\mu^+ \mu^-)$ in $(0.5 - 0.7)$ GeV window
(cascade decay of $\psi(2S)$)

Background Sources

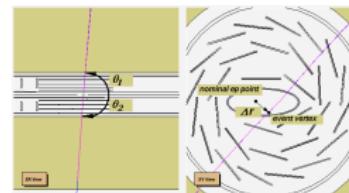
- QED di-muons (like $\gamma^* \gamma^* \rightarrow \mu^+ \mu^-$) from the Bethe-Heitler process



- J/ψ and $\psi(2S)$ mesons production with the dissociation of the proton

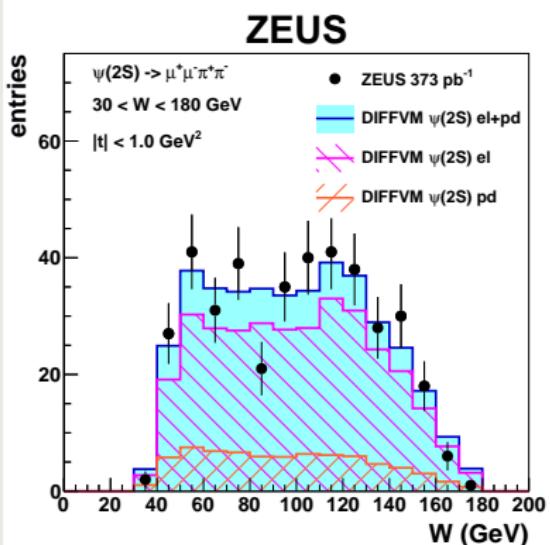


- Cosmic muons can mimic $\mu^+ \mu^-$ pairs when passing close to the interaction point

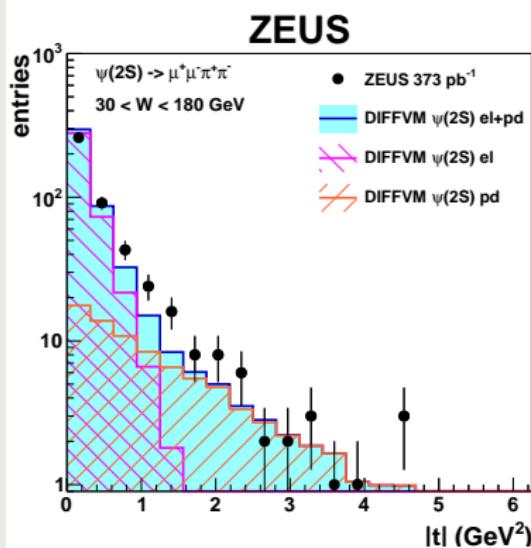


4-prongs: W and $|t|$ distributions: $\psi(2S)$ mass window

W : $3.4 < M(\mu^+ \mu^- \pi^+ \pi^-) < 4.0$ GeV



| t |: $3.4 < M(\mu^+ \mu^- \pi^+ \pi^-) < 4.0$ GeV



- proton dissociation dominates for $|t| > 1.0 \text{ GeV}^2$
 - proton dissociative fraction: $f_{p,diss} = 0.16 \pm 0.01$ ($|t| < 1.0 \text{ GeV}^2$) from t -spectra fit

- Monte Carlo

DIFFVM – A Monte Carlo Generator for Diffractive Processes in ep Scattering.

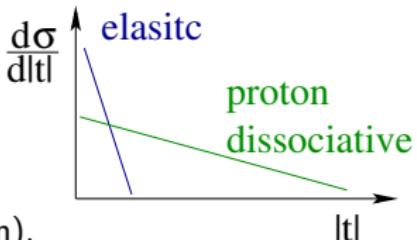
B. List

CERN -EP/OPAL-,
 CH-1211 Genève 23, Switzerland
 Benno.List@cern.ch

A. Mastroberardino

Calabria University, Physics Dept.,
 Cosenza, Italy
 mastrobe@vxdesy.desy.de

- soft diffractive processes in the Regge framework and Vector Dominance Model
- $\frac{d\sigma}{dQ^2} \propto \frac{1}{(1+Q^2/M_Y^2)^{1.5}}$
- $\frac{d\sigma}{d|t|} \propto W_{\gamma p}^{4\epsilon} e^{-b|t|}$ ($4\epsilon = \delta$) (elastic)
- $\frac{d^2\sigma}{d|t|dM_Y^2} \propto W_{\gamma p}^{4\epsilon} e^{-b'|t|} M_Y^{-\beta}$ (p.diss)
- $\frac{d\sigma}{dM_Y^2} \sim \frac{f(M_Y^2)}{M_Y^{2(1+\epsilon)}}$ for $M_Y^2 < 3.6 \text{ GeV}^2$ (p resonance region),
 $\frac{d\sigma}{dM_Y^2} \sim \frac{1}{M_Y^{2(1+\epsilon)}}$ for $M_Y^2 \geq 3.6 \text{ GeV}^2$ (continuum region)
- assuming SCHC: s-channel helicity conservation



GRAPE-Dilepton

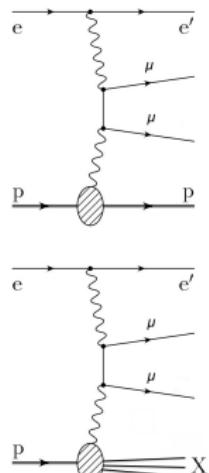
(Version 1.1)

A generator for dilepton production in ep collisions

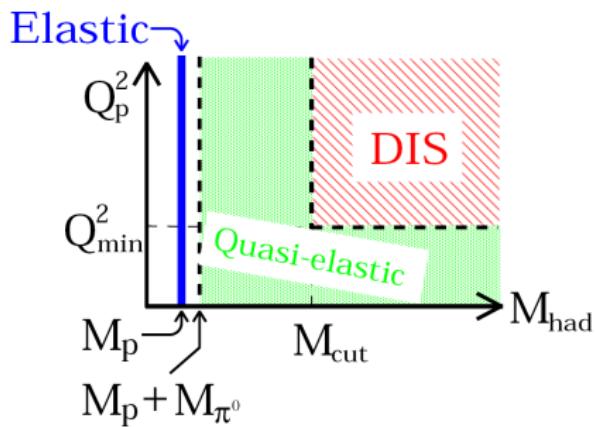
Tetsuo Abe

Department of Physics, University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-8654, Japan

- based on the **exact matrix elements** in the electroweak theory at tree level via $\gamma\gamma$, γZ^0 , Z^0Z^0
and via photon internal conversion (QED Compton)
- **Feynman amplitudes** are generated by the automatic calculation system **GRACE**
- **proton vertex** covers the whole kinematical region
- interface to PYTHIA and SOPHIA
→ complete hadronic final state
- **covers elastic, quasi-elastic and DIS processes**



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



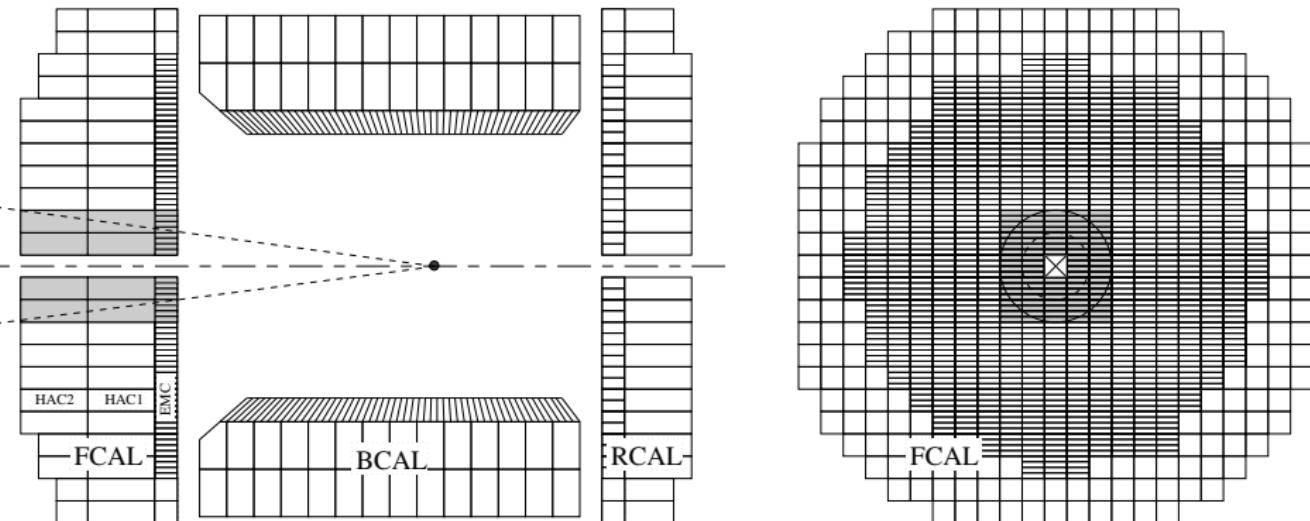
Important for the shape of the BH $M_{\mu^+\mu^-}$ spectrum (sidebands)
and for the BH t -dependence: low t - elastic BH, higher t - QEL BH

- Tuning of DIFFVM Monte Carlo

- Reweighting of MC sample at generator level
- $|t|$ dependence: $\sim \exp(-b|t|)$, generated with $b_{el} = 4.0$, $b_{pd} = 1.0$ reweighted to:
 $b_{el} = 4.6 \pm 0.3$, $b_{pd} = 1.0 \pm 0.1$ (JPSI)
 $b_{el} = 4.3 \pm 0.7$, $b_{pd} = 0.7 \pm 0.2$ (PSI2S)
- shrinkage added by reweighting: $b = b_0 + 4.0\alpha' \log(W/W_0)$;
 $\alpha' = 0.12 \pm 0.04$ GeV $^{-2}$, $W_0 = 90$ GeV (elastic only)
- W dependence: $\sigma \sim W^\delta$,
generated with $\delta = 0.88$ for both elastic and p.diss
reweighted to:
 $\delta_{el} = 0.67 \pm 0.10$, $\delta_{pd} = 0.42 \pm 0.15$ (JPSI)
 $\delta_{el} = 1.10 \pm 0.20$, $\delta_{pd} = 0.70 \pm 0.30$ (PSI2S)
- M_Y dependence: $\sim \frac{1}{M_Y^\beta}$, generated with $\beta = 2.5$
reweighted to $\beta = 2.4 \pm 0.3$ (both JPSI and PSI2S, p.diss only)
- all parameters are subject to systematics checks

- extracting fractions of proton dissociation

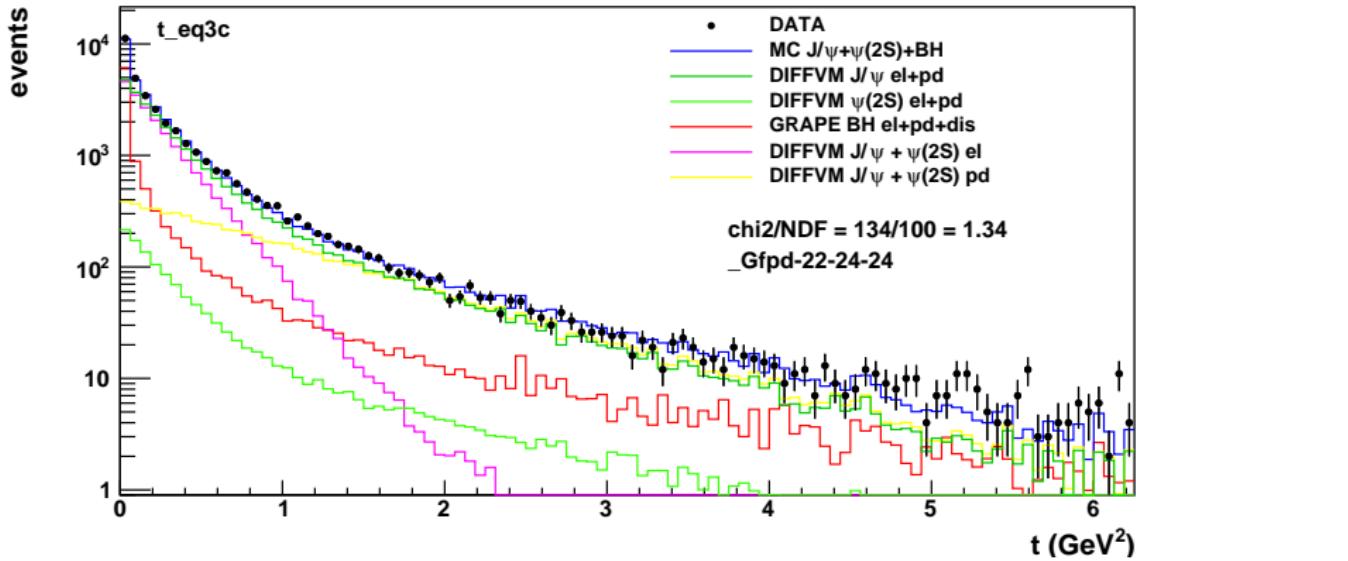
Proton dissociation taggers



- Energy in forward cone to **suppress p.diss events**: $\theta_{max} = 0.12 \text{ rad}$
- using EFO : “Energy Flow Objects” (trackers + CAL info):

$$\left(\sum_{EFOs} E(\theta_{EFO} < \theta_{max}) \right) < 1 \text{ GeV}$$

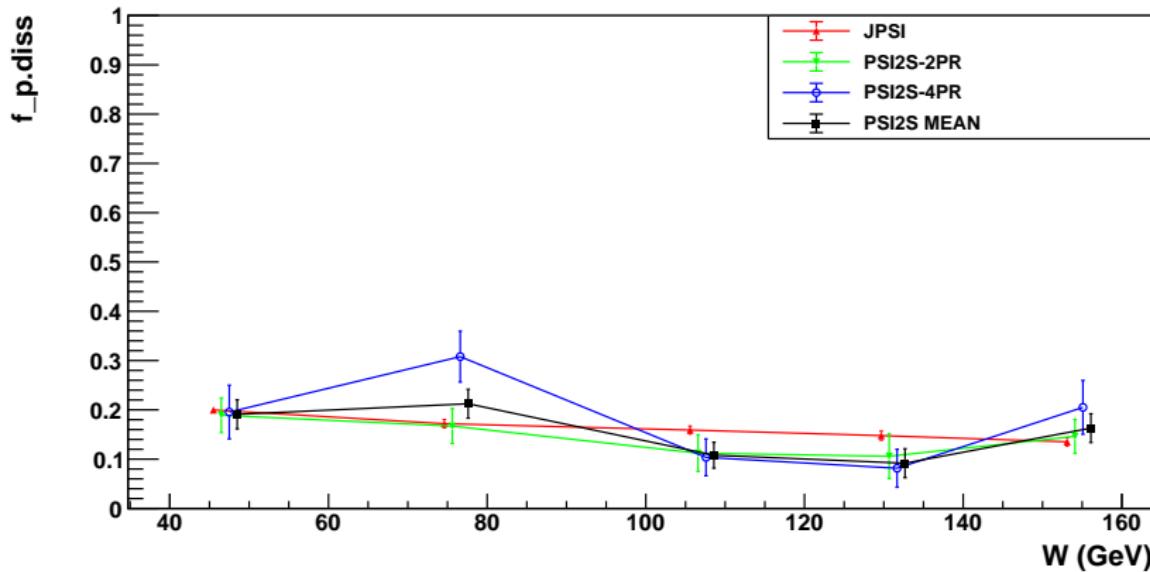
2-prongs: $|t|$ distribution: all 2-prong events



- spectra like this are used to evaluate the p.diss fractions
(use longer “lever arm” then integrate it up to $|t| = 1.0 \text{ GeV}^2$)
- using root package TFractionalFitter (TFF)
- fitted $f_{p.\text{diss}} = 0.17$ and $= 0.16$ (JPSI and PSI2S, BH subtracted)
- p.diss take over elastic around $\sim 1 \text{ GeV}^2$ (yellow and magenta histos)

$f_{p.diss}$ fractions in W bins (TFF estimator)

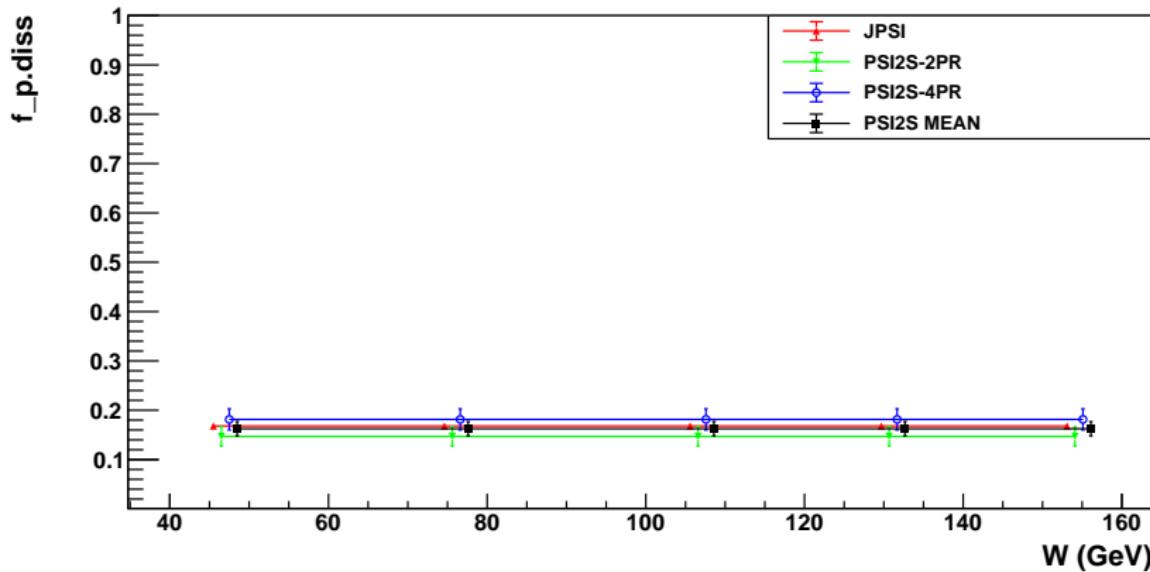
fraction $f_{p.diss}$: JPSI and PS12S 2PR, 4PR vs. W



- average value $\sim 17\%$ JPSI and $\sim 16\%$ PS12S (mean)
- compatible results for 2- and 4-prong channels, no W dependence
- black:** weighted mean for PS12S 2- and 4-prong
- bigger fluctuations for PS12S 2- and 4-prongs

$f_{p.diss}$ fractions in W bins (TFF estimator)

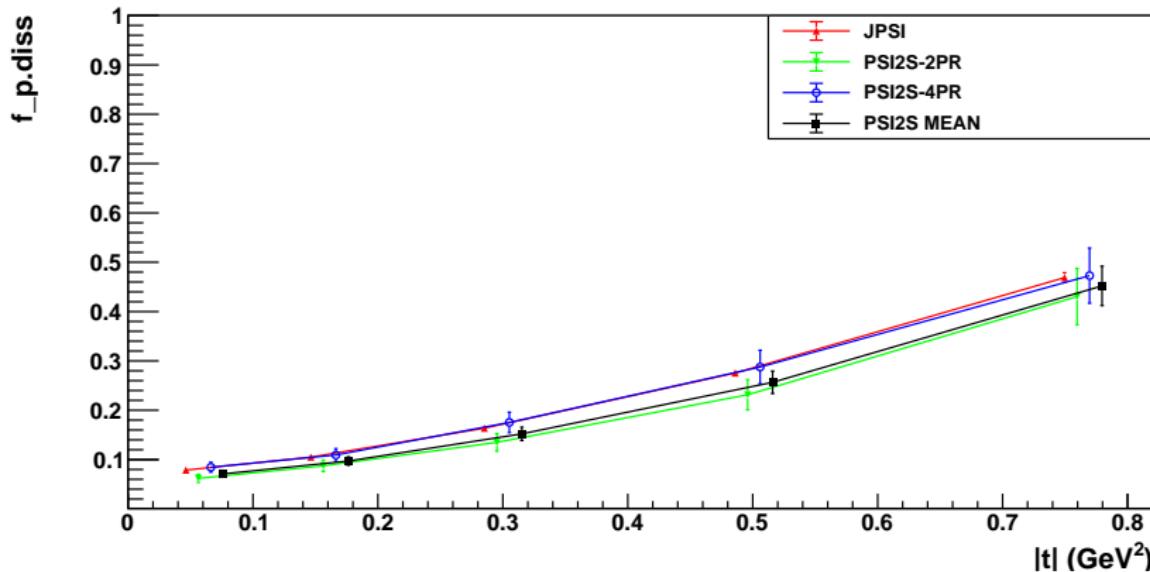
fraction $f_{p.diss}$: JPSI and PSI2S 2PR, 4PR vs. W



- average value $\sim 17\%$ JPSI and $\sim 16\%$ PSI2S (mean)
- black:** weighted mean for PSI2S 2- and 4-prong (used in analysis)
- for R analysis: the same mean value is used for all W bins**
- no significant impact on final ratio R ($f_{p.diss}$ fractions cancels out)

$f_{p.diss}$ fractions in $|t|$ bins (TFF estimator)

fraction $f_{p.diss}$: JPSI and PS12S 2PR, 4PR vs. $|t|$



- compatible results for 2- and 4-prong channels
- black: weighted mean for PS12S 2- and 4-prong (used in analysis)
- negligible effect on final R analysis ($f_{p.diss}$ fractions cancels out)
- bigger impact on systematics for large $|t|$ due to the b -slope variation !

- **Modeling of nucleon resonance states**
- (low M_Y proton dissociation)

- $\frac{d\sigma}{dM_Y^2} \sim \frac{1}{M_Y^{2(1+\epsilon)}}$ for $M_Y^2 \geq 3.6 \text{ GeV}^2$ (continuum region)
- $\frac{d\sigma}{dM_Y^2} \sim \frac{f(M_Y^2)}{M_Y^{2(1+\epsilon)}}$ for $M_Y^2 < 3.6 \text{ GeV}^2$ (p resonance region)
- $f(M_Y^2)$ from the fit the p.diss cross section on deuterium:
 $pD \rightarrow YD$ (Phys. Rep. 101 (3) (1983), 169)
- for $M_Y < 1.9 \text{ GeV}$ several resonances are included
(Pomeron carries quantum numbers of the vacuum ($I=0, G = P = C = +$)
only N^{*+} states with $J^P = \frac{1}{2}^+, \frac{3}{2}^-, \frac{5}{2}^-, \dots$)
- $N^{*+} = N(1440), N(1520), N(1680), N(1700)$
- N^{*+} decays into: $N\pi, \Delta\pi, N\rho, N\pi\pi$ included (BR from PGD 1992)
- N^{*+} decays isotropically in their rest frame
- dissociation in the continuum state carried by JETSET
(splitting proton into $q - \bar{q}$ system, q couples to IP , leaving $\bar{q}q$ spectator)

Modeling of nucleon resonance state: GRAPE

- $d\sigma \sim L_{\mu\nu} W^{\mu\nu}$

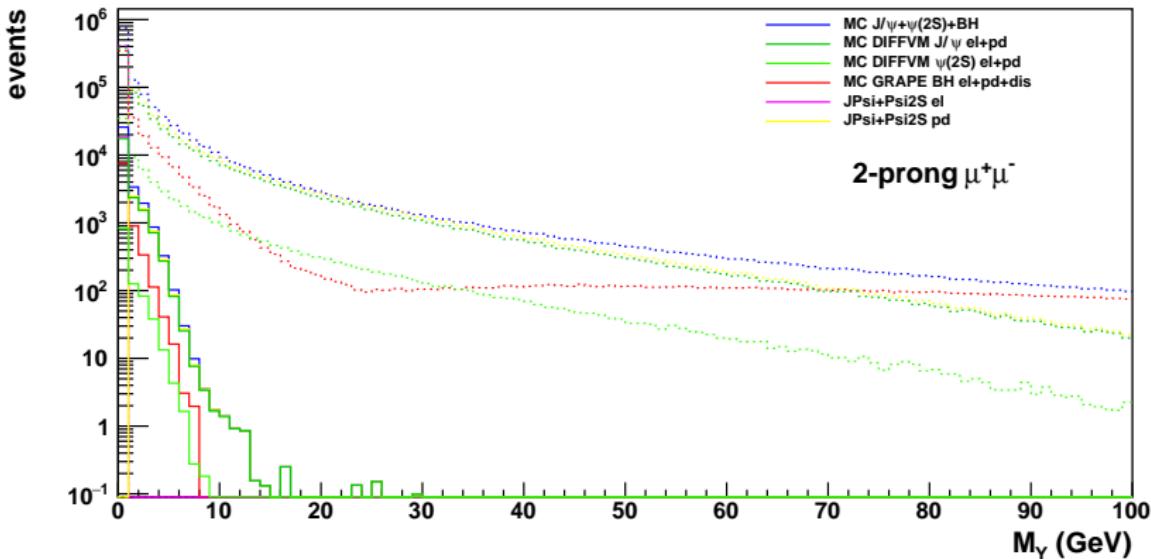
- hadron tensor:

$$W^{\mu\nu} = W_1 \left(-g^{\mu\nu} + \frac{q^\mu q^\nu}{q^2} \right) + W_2 \frac{1}{M_P^2} \left(p_P^\mu - \frac{p_P \cdot q}{q^2} q^\mu \right) \left(p_P^\nu - \frac{p_P \cdot q}{q^2} q^\nu \right)$$

- $W_{1,2}(Q_P^2, M_{had})$ are proton electromagnetic structure functions
- for $M_{had} < 2 \text{ GeV}$ $W_{1,2}$ parameterized by Brasse et al. (Nucl. Phys. **B 110** (1976) 413.) (resonance region)
- for $M_{had} > 2 \text{ GeV}$ $W_{1,2}$ parameterized by ALLM97 (hep-ph/9712415) (continuum)
- both parameterizations from **fits to experimental total $\gamma^* p$ cross sections**
- exclusive hadronic final state generated by SOPHIA
- (plus DIS di-leptons diagrams, in the framework of QPM, using PDF's)

MC generator level: M_Y before and after selection cuts

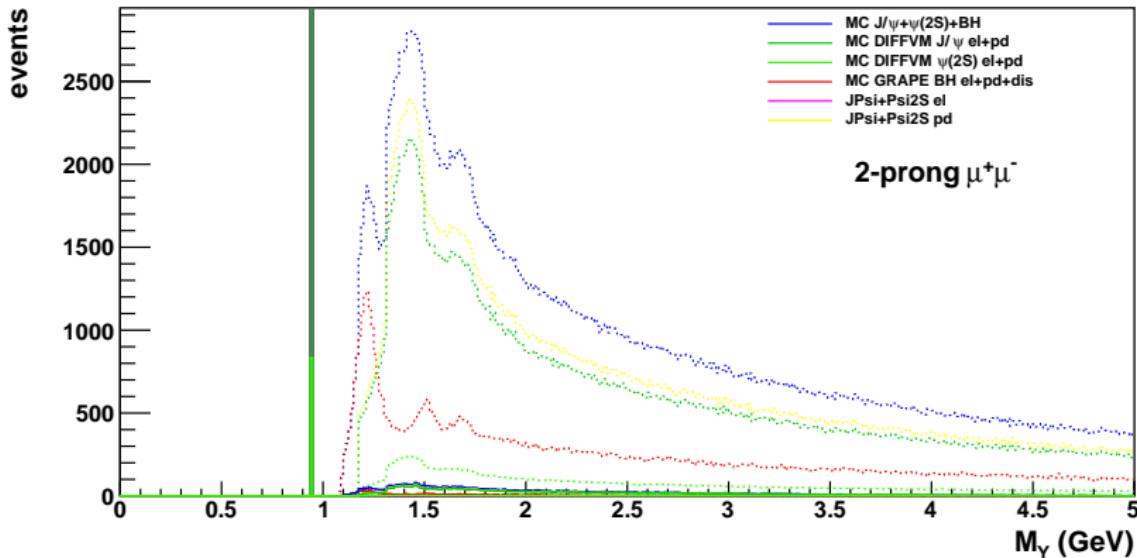
M_Y gener before and after cuts



- M_Y at generator level (not measured quantity ! \rightarrow lost in beam-pipe)
- before and after selection cuts
- **GRAPE (BH) does include DIS scattering \rightarrow rise of xsec. for large M_Y**
- DIFFVM in DIS mode generates only **electroproduction**
(with proton dissociation, “rapidity gap events”) \rightarrow this is OK

MC generator level: zoom at low $M_Y < 5$ GeV (lin scale)

M_Y gener before and after cuts

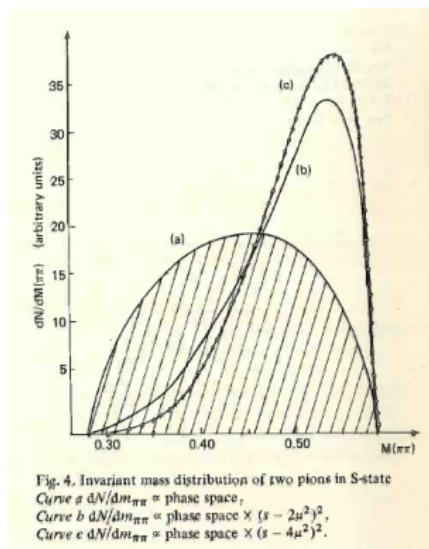


- different structure of nucleon resonances between GRAPE and DIFFVM (!?)
- which is right ?
- how much it is important for p.diss BG subtraction ?

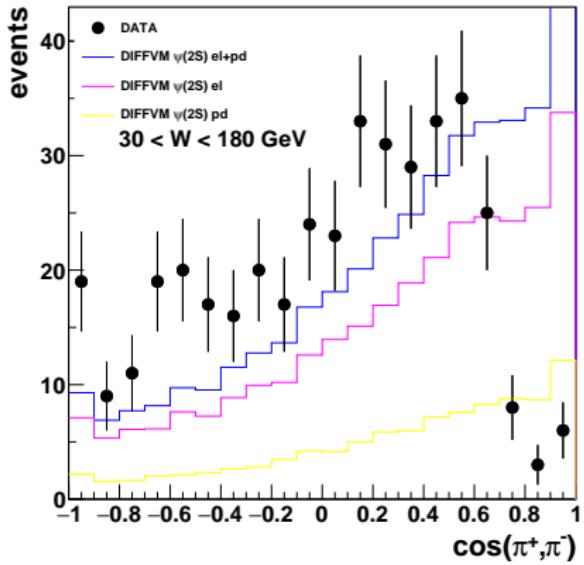
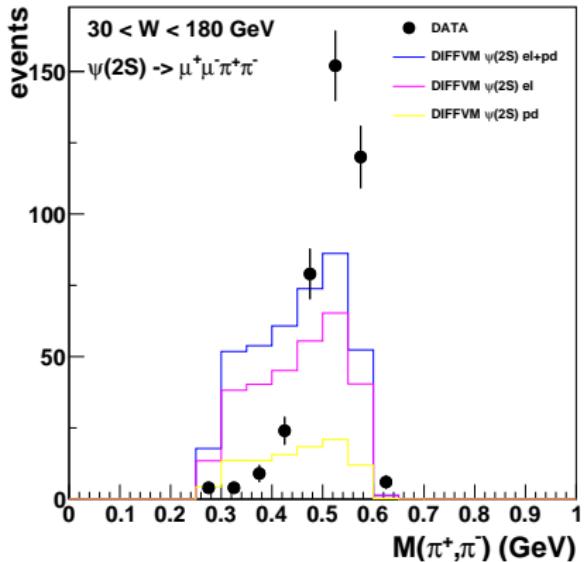
- Pions phase space reweighting

Pions phase space reweighting (DIFFVM 4-prongs)

- $weight = (M(\pi^-, \pi^+)^2 - 4.0 * M_\pi^2)^2$
 - ref: Phys.Lett.B61.1976.183.pdf
 - final $\pi^+\pi^-$ interaction is not in pure S-state
 - → for the impact of this correction see next 2 pages

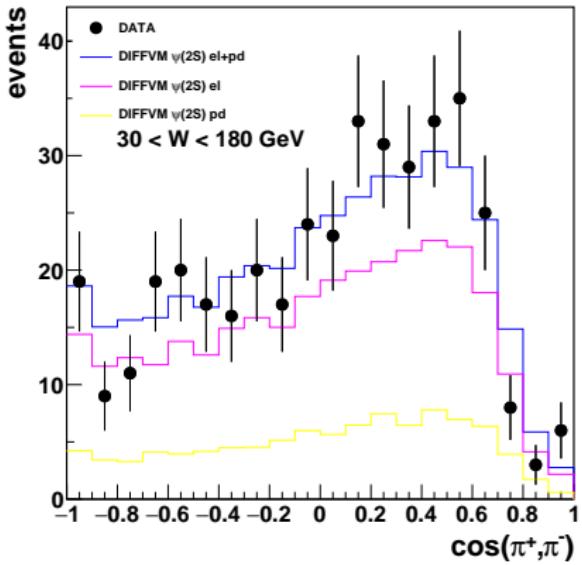
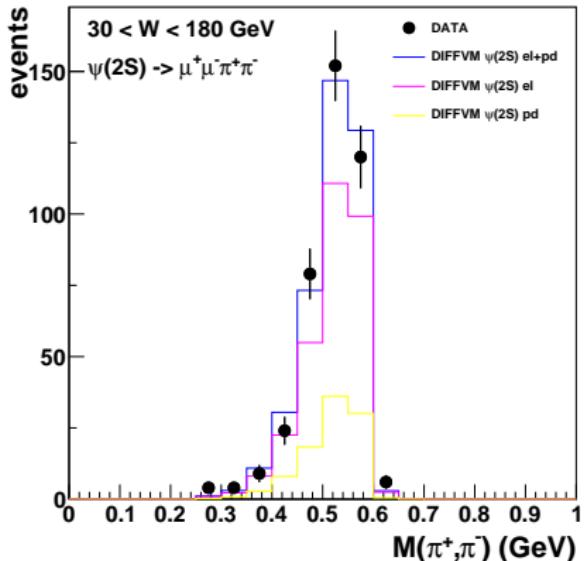


4-PRONGS: $M(\pi^-, \pi^+)$, $\cos(\pi^-, \pi^+)$



- $\psi' \rightarrow J/\psi + \pi^+ \pi^-$
 - $M(\pi^-, \pi^+), \cos(\pi^-, \pi^+)$
 - DIFFVM MC before pions phase space reweighting

4-PRONGS: $M(\pi^-, \pi^+)$, $\cos(\pi^-, \pi^+)$

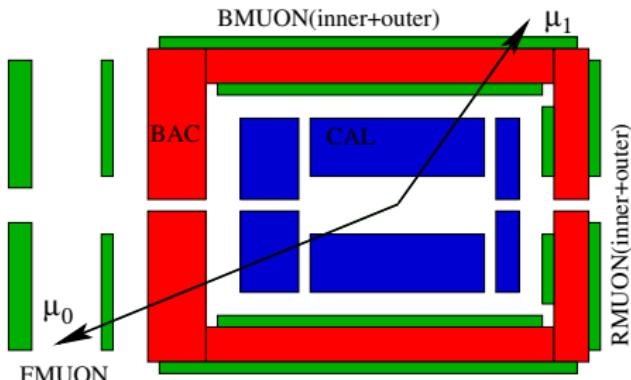


- $\psi' \rightarrow J/\psi + \pi^+ \pi^-$
 - $M(\pi^-, \pi^+)$, $\cos(\pi^-, \pi^+)$
 - DIFFVM MC after pions phase space reweighting

- Muon effic. corrections

Muon effic. corrections: TAG and PROBE

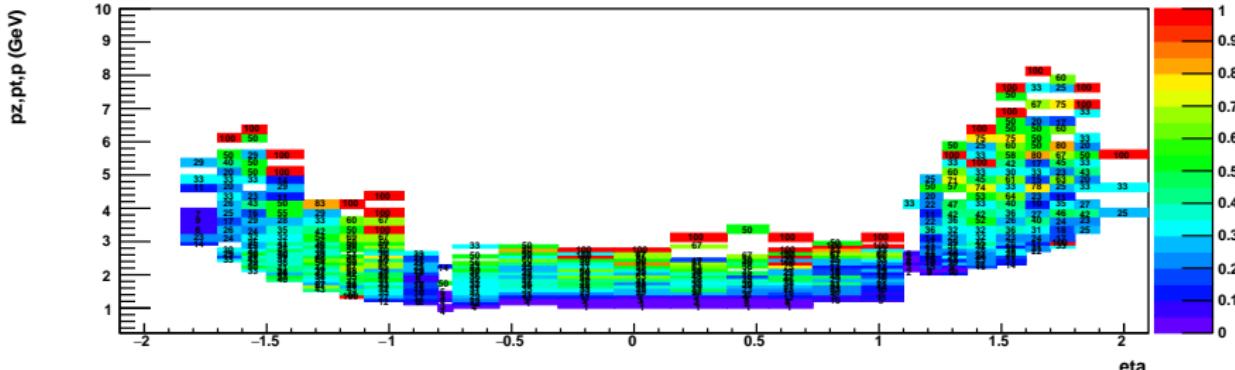
- TAG: “the triggering” muon
- PROBE: “the tested” muon
- effic in given $(pt_{\text{eff}}^j, \eta^j)$ bin:
 $\epsilon = N_{\text{PROBE}}^j / N_{\text{TAG}}^j$



- one step correction for (FLT and SLT and TLT and off-line REC)
- separate maps for F/B/R/MUO, BAC and CAL (off-line only)
- evaluated for single muon in (pt_{eff}, η) bins, where as pt_{eff} is used:
(motivated by the CAL/BAC geometry and scaling of the muon path length)
 - p in Forecap
 - p_t in Barrel
 - p_z in Rearcap
- proper identification of the triggering muon is crucial
- → the DATA/MC ratio delivers the correction weight: $\epsilon_x = \frac{\epsilon_{\text{DATA}}}{\epsilon_{\text{MC}}}$

Muon correction maps: (p_z, p_t, p vs. η) - DATA

MUO DATA eff ALL



- **muon tomography**
- probability (%) to fire FLT-SLT-TLT-REC chain by single muon on $(p_z, p_t, p; \eta)$ grid
- X-axis (along eta): Rear-MUO, Barrel-MUO, Forward-MUO detectors
- **only events with $M(\mu^+, \mu^-) < 6$ GeV**
(ie. in the phase space range of di-muon mass fits)
- current choice for p_z, p_t, p grid: **100 MeV per bin ($p_{\text{eff}} < 3$ GeV), 250 MeV per bin ($p_{\text{eff}} > 3$ GeV)**
- size of the grid is subject to systematics