# $\psi(2S)$ to $J/\psi(1S) \to \mu^+\mu^-$ exclusive xsection ratio with ZEUS (case study)

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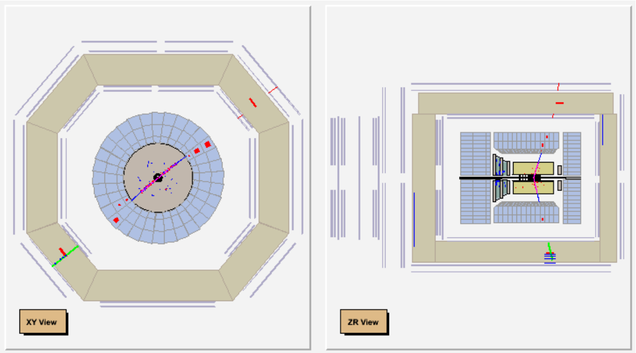
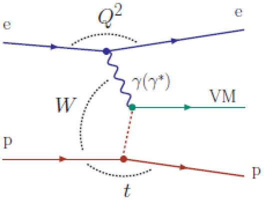
*CFNS Workshop: Hera 4 EIC, (online), 8 – 10 June 2022*

- **HERA II DATA:** $\mathcal{L} = 373\ \text{pb}^{-1}$ (2003 - 2007)
- **Investigated decay channels:**
  - $\psi(2S) \to \mu^+\mu^-, \quad \psi(2S) \to J/\psi + \pi^+\pi^-, \quad J/\psi(1S) \to \mu^+\mu^-$
- exclusive (elastic) photoproduction sample
- **kinematic range (analysis phase space):**
  - $30 < W < 180$ GeV (acceptance of muon chambers: $<\sim$ 300 GeV, HERA c.m.s.)
  - $|t| < 1.0\ \text{GeV}^2$ (elastic to proton dissociative ratio)
  - $Q^2 < 1\ \text{GeV}^2$ (median $Q^2 \approx 3 \times 10^{-5}\ \text{GeV}^2$) ($e'$ acceptance)
- differential measurement in 5 $W$ bins and 5 $|t|$ bins
  $\to$ specific issues at the edge of the phase space

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



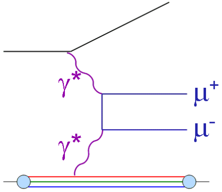

Exclusive process, reaction mediated by exchange of colorless object;
**proton stays intact.**

$J/\psi$ 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:

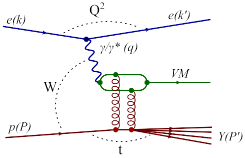
Photoproduction ($Q^2 < 1$ GeV$^2$): two or four charged particles and nothing else
$\Longrightarrow$ **experimental challenge: triggering on soft muons**
(Electroproduction ($Q^2 > 1$ GeV$^2$): scattered electron also visible in the detector)

# Background Sources

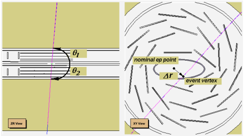
- QED di-muons (like $\gamma^*\gamma^* \to \mu^+\mu^-$) from the Bethe-Heitler process




- $J/\psi$ 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



# Monte Carlo

- **Signal MC:** DIFFVM (exclusive/elastic)
- **Background MC:** DIFFVM (proton dissociation)
- **Background MC:** GRAPE
  (Bethe-Heitler continuum $\mu^+\mu^-$ pairs)

# Signal Monte Carlo: DIFFVM

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

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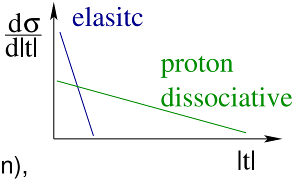
- soft diffractive processes in the Regge framework and Vector Dominance Model
- $\frac{d\sigma}{dQ^2} \propto \frac{1}{(1+Q^2/M_V^2)^{1.5}}$
- $\frac{d\sigma}{d|t|} \propto W_{\gamma p}^{4\epsilon} e^{-b|t|}$ $(4\epsilon = \delta)$ (elastic)
- $\frac{d^2\sigma}{d|t|dM_Y^2} \propto W_{\gamma p}^{4\epsilon}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



# Lesson learned/to be learned:

## Signal Monte Carlo

- DIFFVM OK for efficiency/acceptance corrections
- requires tuning of many free parameters
- oversimplified parameterization (enough for moderate $|t|$ in *ep* scattering)
- more realistic description of diffraction pattern will be welcome :).

GRAPE-Dilepton
(Version 1.1)
A generator for dilepton production in *ep* collisions

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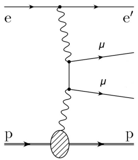
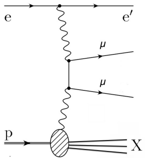
- based on the exact matrix elements in the electroweak theory at tree level via $\gamma\gamma$, $\gamma Z^0$, $Z^0 Z^0$
  and via photon internal conversion (QED Compton)
- Feynman amplitudes are generated by the automatic calculation system GRACE
- **proton vertex** covers the whole kinematical region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



# Lesson learned/to be learned:

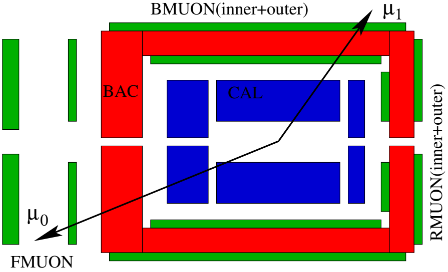
## Bethe-Heitler continuum di-muon pairs

- LO MC (like GRAPE) sufficient for *ep* scattering
- not sure for *eA* collisions
  (stronger electric field around heavy nuclei)
- NLO, multi-photon effect important (?)

- **Muon efficiency corrections**

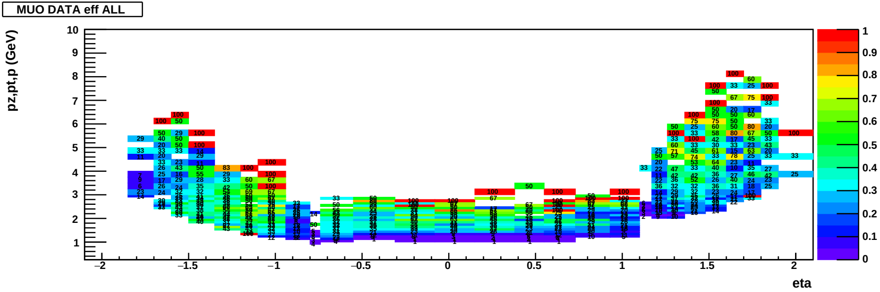
# Single muon efficiency corrections: TAG and PROBE

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



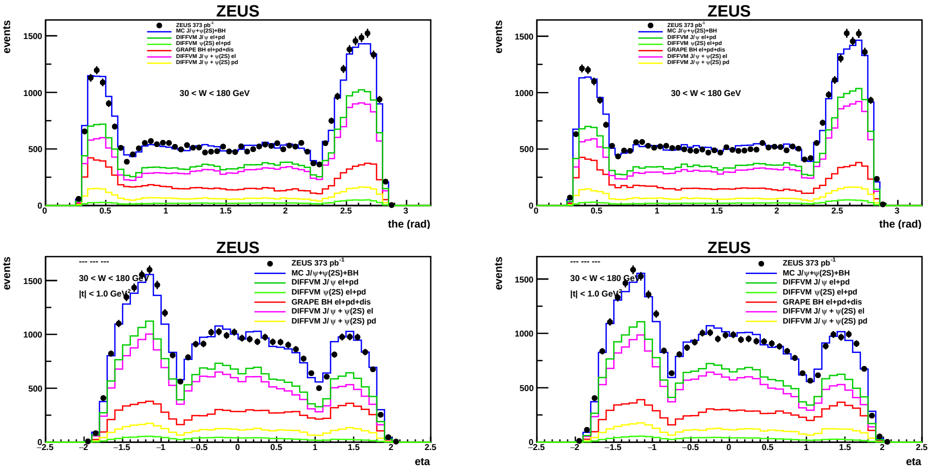

- one step correction for (FLT and SLT and TLT and off-line REC)
- separate maps for F/B/R/MUO, BAC and CAL (off-line only)
- evaluated for single muon in $(pt_{eff},\eta)$ bins, where as $pt_{eff}$ is used:
  (motivated by the CAL/BAC geometry and scaling of the muon path length)
  - $p$ in Forecap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

# Muon correction maps: ($p_z, p_t, p$ *vs.* $\eta$) - DATA



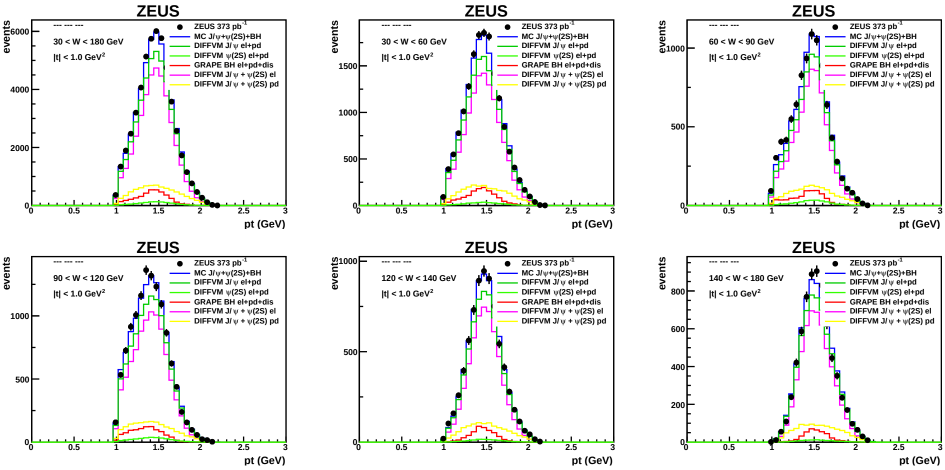

- **muon tomography (+ muon range)**
- probability (%) to fire FLT-SLT-TLT-REC chain by single muon on ($p_z, p_t, p; \eta$) grid
- X-axis (along eta): Rear-MUO, Barrel-MUO, Forward-MUO detectors
- only events with $M(\mu^+, \mu^-) < 6$ GeV
  (ie. in the phase space range of di-muon mass fits)
- $p_z,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

# $\theta$ and $\eta$ distribution for $\mu^+$ and $\mu^-$




- $\theta$ and $\eta$ distribution for muon tracks ($\mu^+$ and $\mu^-$, $\eta \in (-2, 2)$)
- **after MC tuning and muon corrections**
- well reproduced acceptance and efficiency of the detector

# 2-prongs: JPSI mass window: $p_t^{\mu^\pm}$ in $W$ bins




- ALL events and in W1, W2, W3, W4, W5 bins
- **Jacobian peak around** 1.5 **GeV (**$M_{JPSI}/2$**)**
- almost no JPSI (and PSI2S) event loss due to the $p_t^{\mu^\pm} > 1$ GeV cut

## Lesson learned:

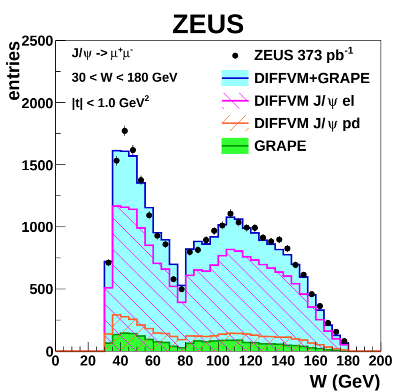
### Triggering on soft muons ($p_T \sim 1 \div 2$ GeV)

- working on the steep edge of the trigger acceptance curve
- muon efficiency corrections extracted from data are crucial (trigger and off-line corrections)
- design the trigger to identify **the triggering muon** on all trigger levels

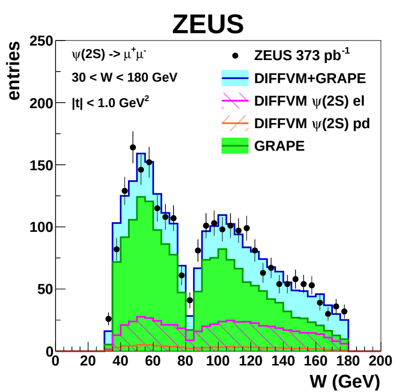
- ***W*** **distributions: 2-prongs**

# 2-prongs: $W$ distributions

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



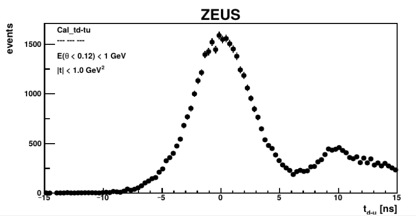

## $W$: $3.4 < M(\mu^+\mu^-) < 4.0$ GeV



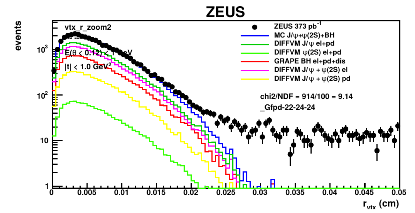

- $W$ range limited by acceptance of muon chambers (for given VM mass)
- dip in $W$ distribution due to the anti-COSMIC cut: $\cos(\mu^+, \mu^-) < -0.985$
- reduced by CAL Up-Down timing cut for MIP clusters

# Lesson learned:

## CAL timing: Down-Up MIP clusters




## transverse distance to the vertex



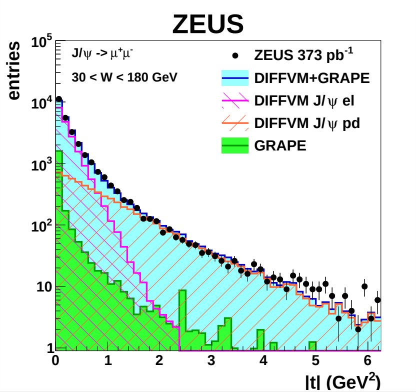

## Reducing the Cosmic muon background

- angular tracking resolution (co-linearity cut !)
- timing cut on CAL MIP clusters

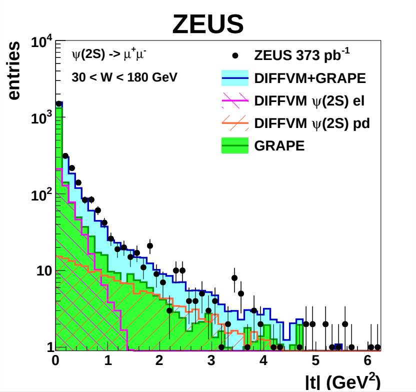
- **$|t|$ distributions: 2-prongs**

# 2-prongs: $|t|$ distributions

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



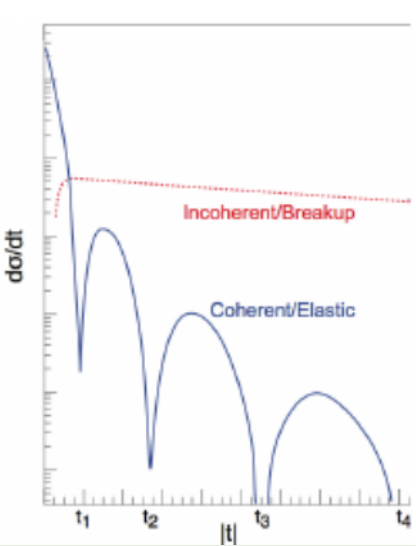

## $|t|$: $3.4 < M(\mu^+\mu^-) < 4.0$ GeV




- single exp() parameterization of elastic and p.diss (DIFFVM MC)
- proton dissociation dominates for $|t| > 1.0$ GeV$^2$
- proton dissociative fraction: $f_{p.diss} = 0.16 \pm 0.01$ ($|t| < 1.0$ GeV$^2$) from $t$-spectra fit
- $\psi(2S)$ channel dominated by Bethe-Heitler continuum $\mu^+\mu^-$ background

# Lesson learned:

## Elastic vs. p-diss *t*-spectra




## Modeling $|t|$-distribution

- single $\exp(-b|t|)$ fit sufficient for *ep* data and moderate $|t|$
- *b*-slopes extracted from data...
- for *eA* expected more complex structure (diffraction pattern):
  - $t = -p_{t,VM}^2$ : tracker resolution !
  - suppression of p-diss BG
- proper description of Bethe-Heitler BG is important

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

# Modeling of nucleon resonance state: DIFFVM

- $\frac{d\sigma}{dM_Y^2} \sim \frac{1}{M_Y^{2(1+\epsilon)}}$ for $M_Y^2 \geq 3.6$ GeV$^2$ (continuum region)
- $\frac{d\sigma}{dM_Y^2} \sim \frac{f(M_Y^2)}{M_Y^{2(1+\epsilon)}}$ for $M_Y^2 < 3.6$ GeV$^2$ ($p$ resonance region)
- $f(M_Y^2)$ from the **fit the the p.diss cross section on deuterium**: $pD \to YD$ (Phys. Rep. **101** (3) (1983), 169)
- for $M_Y < 1.9$ GeV several resonances are included (Pomeron carries quantum numbers of the vacuum (I=0, G = P = C= +) only $N^{*+}$ states with $J^{\mathcal{P}} = \frac{1}{2}^+, \frac{3}{2}^-, \frac{5}{2}^-, ...$)
- $N^{*+} = N(1440), N(1520), N(1680), N(1700)$
- $N^{*+}$ 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 $q - qq$ system, $q$ couples to $\mathbb{P}$, leaving $qq$ spectator)

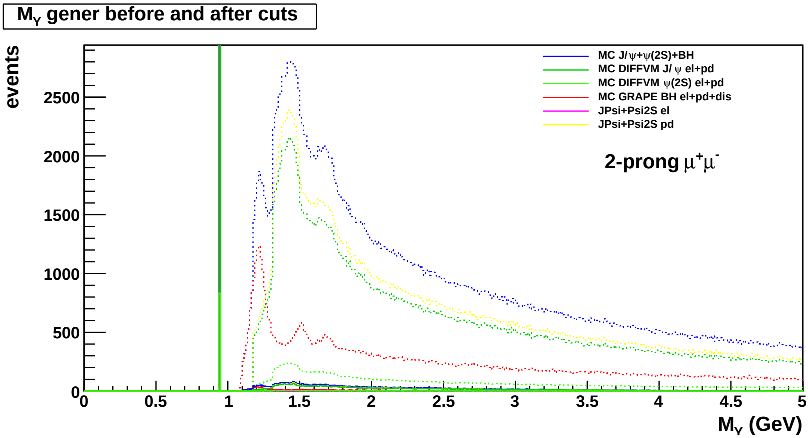
# Modeling of nucleon resonance state: GRAPE

- $d\sigma \sim L_{\mu\nu} W^{\mu\nu}$
- 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 $M_{had} < 2$ GeV $W_{1,2}$ parameterized by Brasse at al. (Nucl. Phys. **B 110** (1976) 413.) (resonance region)
- for $M_{had} > 2$ 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: zoom at low $M_Y < 5$ GeV (lin scale)




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

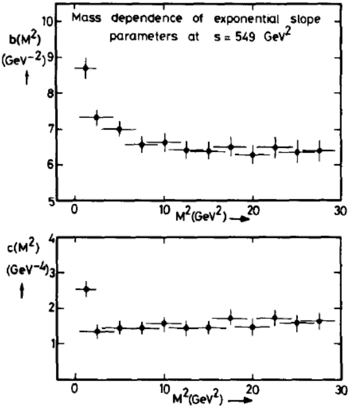
# Lesson learned/to be learned:

## Modeling of nucleon resonances $N^*$, etc...

- more realistic, unified treatment of nucleon resonances will be required
- feedback from data (?)

- **Modeling of nucleon resonance states**
- (*b*-slope for low $M_Y$ $N^*$ states)

# dependence of p.diss $t$-slopes on $M_Y$



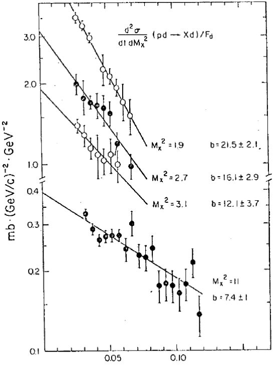
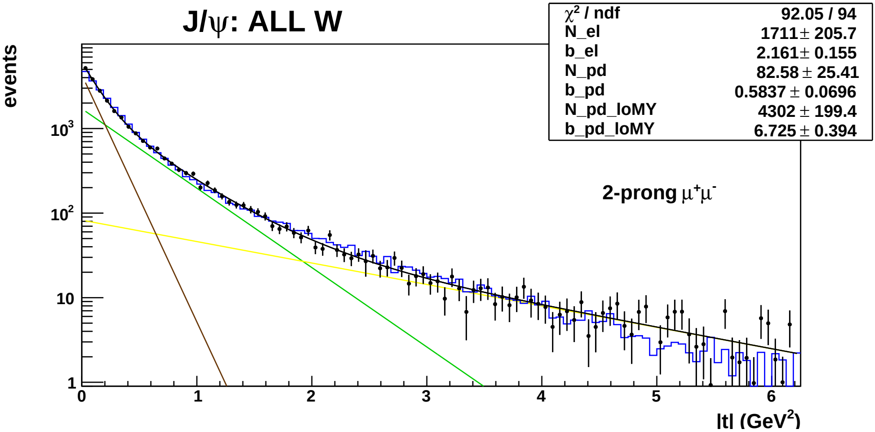



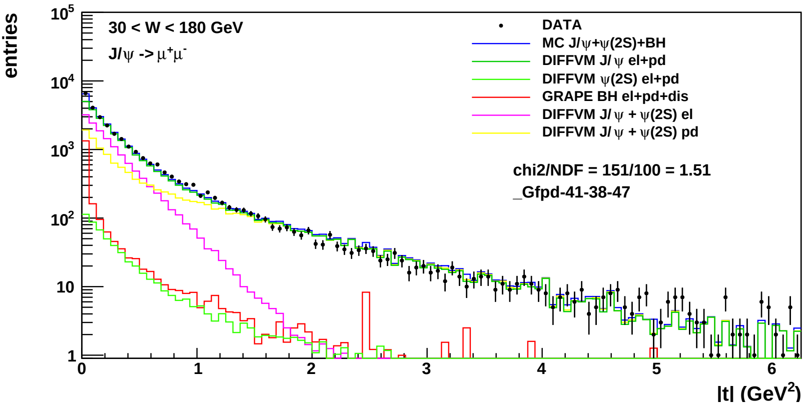

Figure 2 - Differential cross-sections vs. t for pp → Xp, extracted from pd → Xd, at $p_{lab}$ = 275 GeV/c, for $M_x^2$ = 1.9, 2.7, 3.1, and 11 GeV².

$$\frac{d^2\sigma}{dtdM_X^2}(pd \to Xd)$$

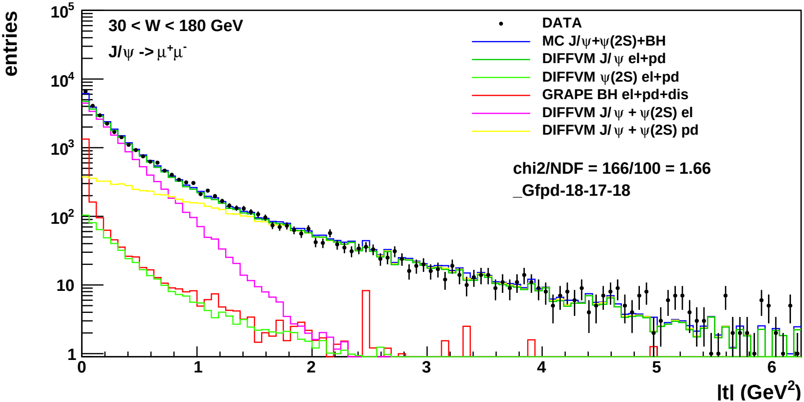
- Fermilab and ISR data: Phys. Rev. **D 14**, 3148 (1976), Nucl. Phys. **B 108**, 1 (1976)
- steeper proton dissociative $t$-spectra for very low $M_Y$ and $|t|$ ($b_{pd} \approx 10 \div 20$ GeV$^{-2}$)
- **effect observed for** $pp$ **(and pd) collisions** (old language: $M_X \to M_Y$)
- is it also present for $\gamma p$ p-dissociative interactions ?
- if yes, it has big impact on the estimation of p.diss fraction (extrapolated from model dependent MC)




- $J/\psi$ mass window, BH background subtracted
- **unconstrained triple** exp() **fit**, all $M_Y <\sim 6$ GeV (elastic selection)
- there is some room for third, steeper component $b_{pd-loMY} \approx 6.5$ GeV$^{-2}$
- but the elastic $b_{el}$ slope becomes very unrealistic: $b_{el} \approx 2$ GeV$^{-2}$




- **constraining the low $M_Y$ component**
- reweighting the resonances $M_Y < 1.9$ GeV to $b_{pd-loMY} = 6.5$ GeV$^{-2}$ (yellow histogram)
- DATA/MC agreement is as good as for two components (see next page)
- ... but the p.diss fraction increases from $\sim 20$ to $\sim 40\%$ (for $|t| < 1$ GeV$^2$)




- “standard” two components model: single exp() for elastic and p.diss
- yellow : p.diss with $b_{pd} = 1.0\ \text{GeV}^{-2}$
- $f_{p.diss} = 18\%\ (|t| < 1\ \text{GeV}^2)$

# Lesson learned/to be learned:

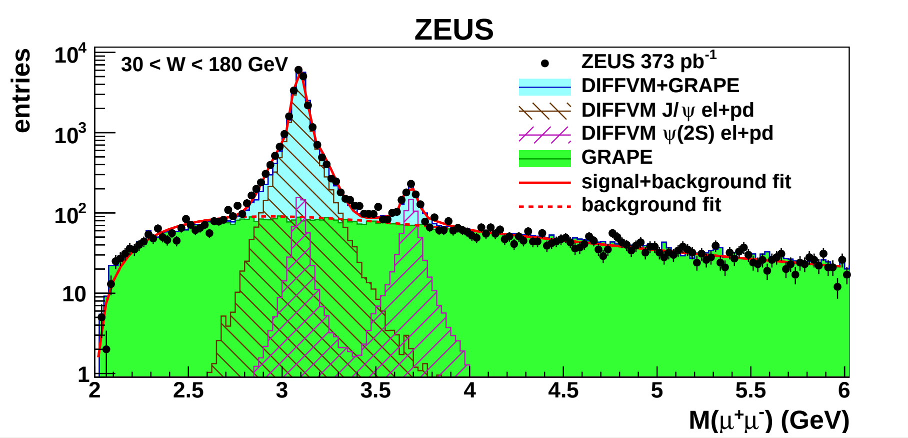
## Modeling of $t$-slope for nucleon resonances $N^*$, etc...

- is the steeper $t$-slope dependence observed for *ep* and *eA* data ?

- **Signal Extraction, Mass spectra**

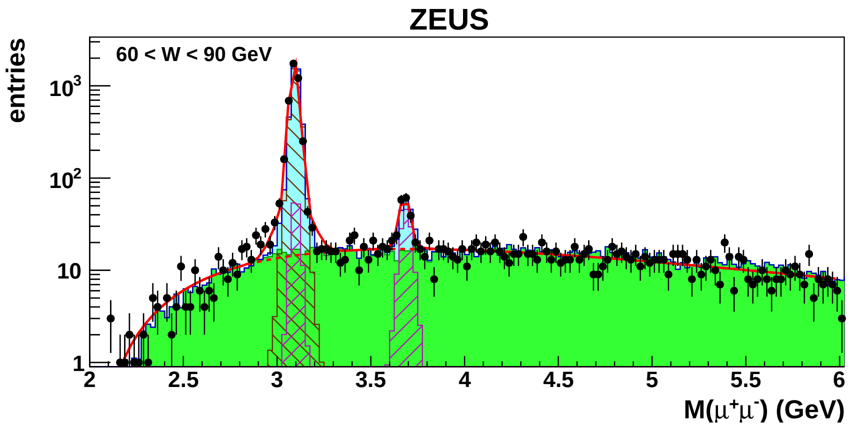
# 2-prongs: dimuon mass spectra

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



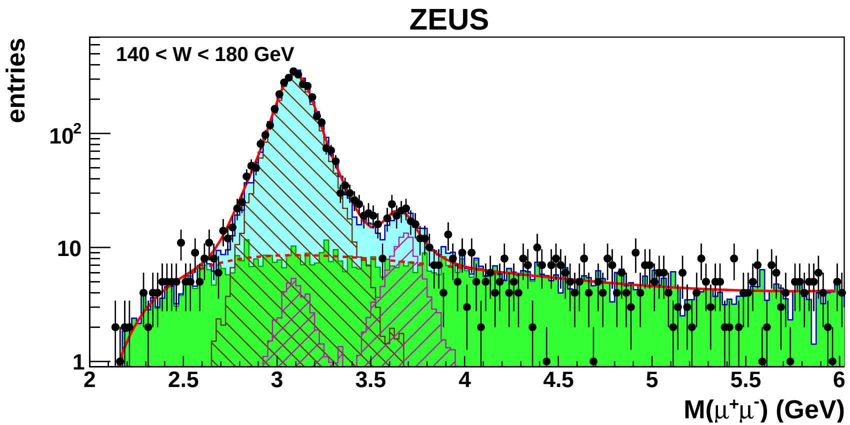

- **full phase space:** $30 < W < 180$ GeV, $|t| < 1.0$ GeV$^2$
- events yield: $\sim 23\,000$ $J/\psi$ and $\sim 700$ $\psi(2S)$
- resonant background under $J/\psi$ peak

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




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

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




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

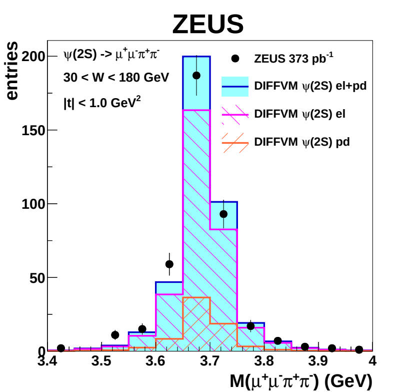
# Lesson learned:

## Tracker resolution

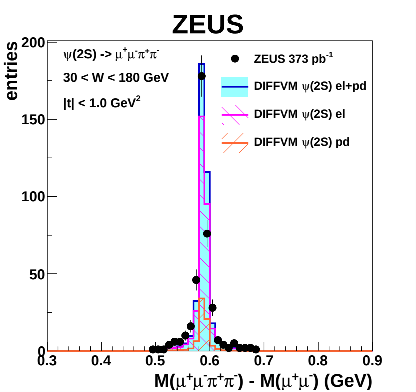
- instrumentation (tracking) close to the beam-pipe very important for high and low $W$ measurement

# 4-prongs: mass spectra: $\psi(2S) \to \mu^+\mu^-\pi^+\pi^-$

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



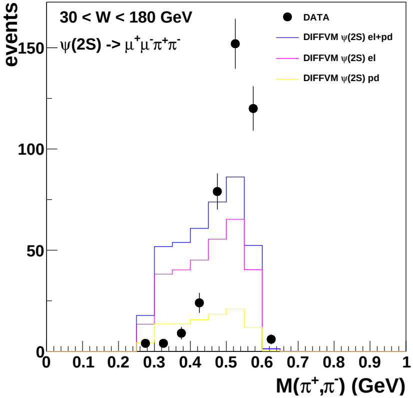

## $M(\mu^+\mu^-\pi^+\pi^-) - M(\mu^+\mu^-)$

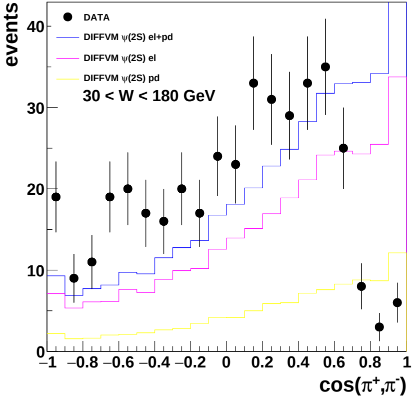



- events yield: $\sim 400\ \psi(2S)$
- better resolution on mass difference $\to$ cascade decay of $\psi(2S)$
- **almost background free channel, but: ...**
- **TAKE CARE: SLOW PIONS are VERY FRAGILE !**

- **(SLOW) Pions phase space reweighting**

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




- $\psi' \to J/\psi + \pi^+\pi^-$
- $M(\pi^-, \pi^+)$, $\cos(\pi^-, \pi^+)$
- DIFFVM MC before 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
- $\rightarrow$ for the impact of this correction see next page

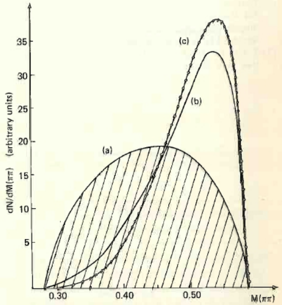
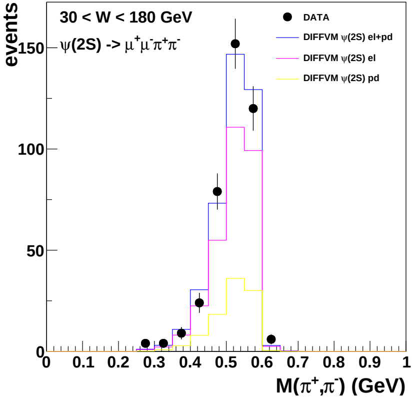
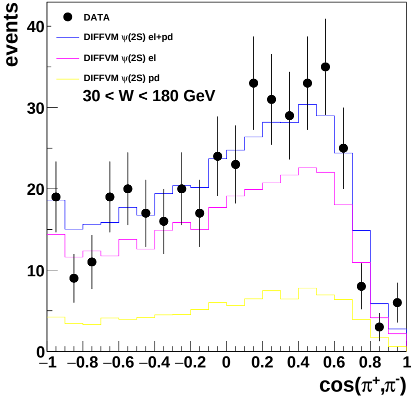



Fig. 4. Invariant mass distribution of two pions in S-state
Curve a $dN/dm_{\pi\pi} \propto$ phase space,
Curve b $dN/dm_{\pi\pi} \propto$ phase space $\times (s - 2\mu^2)^2$,
Curve e $dN/dm_{\pi\pi} \propto$ phase space $\times (s - 4\mu^2)^2$.

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




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

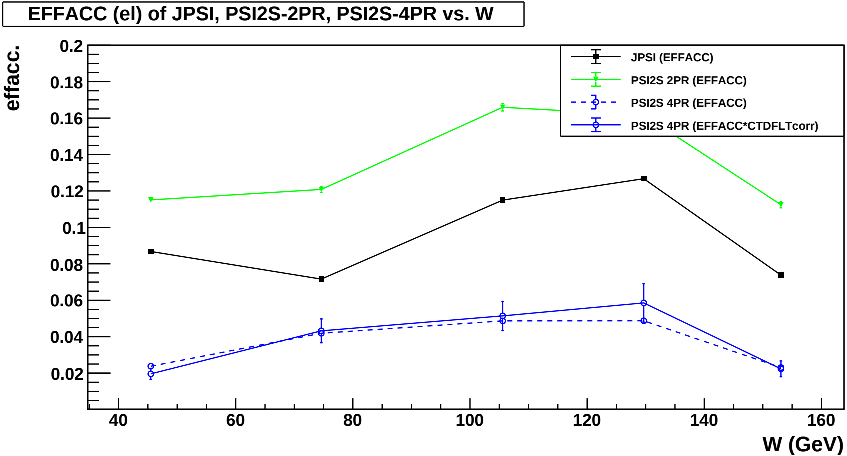
# Lesson learned:

## SLOW PIONS PHASE SPACE: $\psi(2S) \to \mu^+\mu^-\pi^+\pi^-$

- trust and check :)
- after long time wisdom of old generations sometimes dissappear...

- **selection efficiency**

# Acceptance*efficiency in *W* bins: elastic

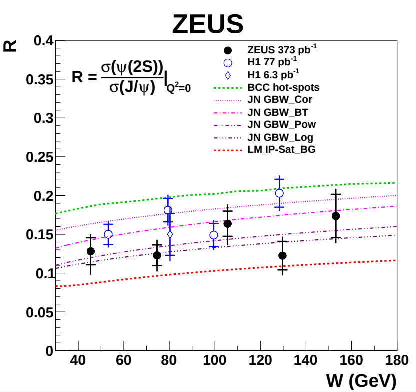



- JPSI, PSI2S 2- and 4-prong (**2 ÷ 16%**)
- Higher di-muon acceptance for higher mass state (PSI2S)
- similar angular coverage for final state di-muons
- second W bin (W2) is the "dip" for di-muon acceptance

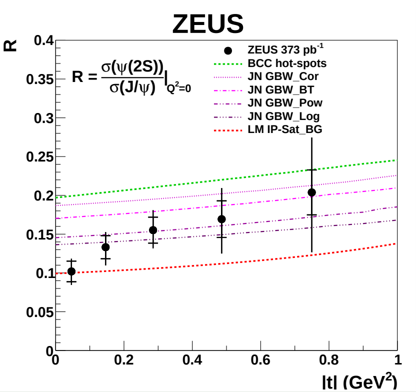
- **Cross section ratio**

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

## $R$ vs. $W$

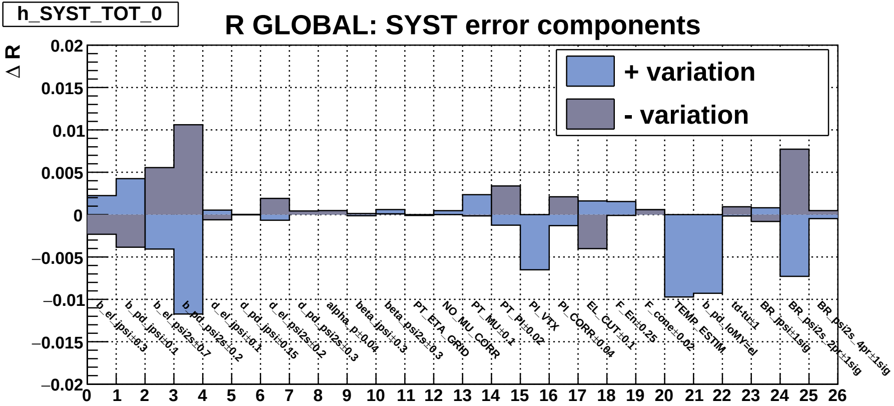



## $R$ vs. $|t|$




- 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)

# $R$: components of global systematic error




- biggest contributions from:
- $b$-slope variation of $t$-dependence (esp. for $b_{pd}$ of $\psi(2S)$) $\rightarrow$ **p.diss fraction**
- event number estimator (MC templates fit instead of Gaussian fit) $\rightarrow$ **BH bckgr.**
- slow pions vertexing $\rightarrow$ **very soft tracks reconstruction**
- $BR(\psi(2S) \rightarrow \mu^+\mu^-)$ $\rightarrow$ **PDG world average...**

# Summary/Conclusions

- case study on exclusive $J/\psi \to \mu^+\mu^-$
- **DIS vs. photoproduction** (trigger challenge)
- Monte Carlo(s) models : tuning of parameters
- **better measurements** of MC parameters needed ($t$-slopes, ...)
- mass resolution vs. $W$ (forward and rear trackers acceptance)
- **proton dissociation** $\to$ **role of forward taggers**
- proton dissociation $\to$ $t$-spectra study (are two $\exp()$ sufficient at low $|t|$ ?)
- to make progress: **precision is needed !**
- **statistic** $\to$ more luminosity
- **systematics** $\to$ better instrumentation (forward detectors, taggers)
- **systematics** $\to$ better theoretical models (MC), ...

# Backup plots

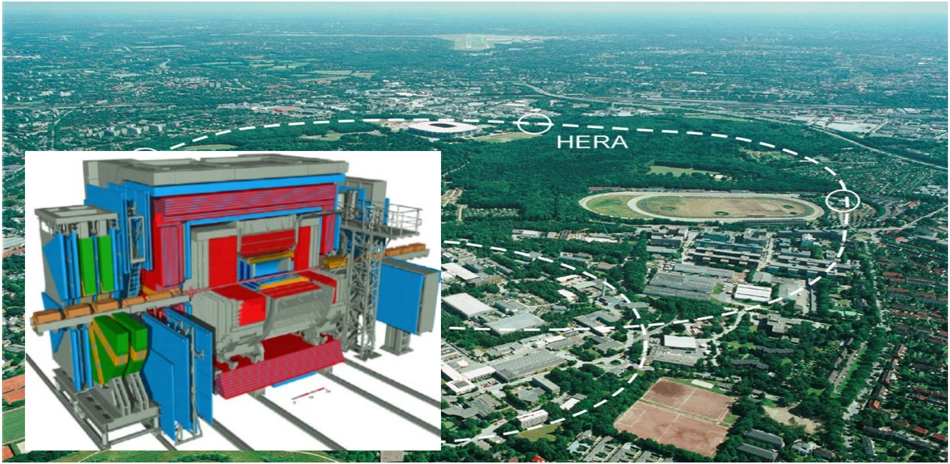
- Backup plots follow...

# Outline

- HERA accelerator, ZEUS experiment
- case study based on new analysis
  ($J/\psi$ to $\psi(2S)$ cross section ratio in exclusive photoproduction, $\mu^+\mu^-$ channel)
- Physics Motivation $\longrightarrow$ see backup plots
- DIS vs. PHP (trigger strategy)
- Data sample, signal and background
- proton dissociation
- cosmic muons
- Monte Carlo, tuning of parameters,
  controlling efficiency/acceptance corrections
- extracting $t$-slopes from data
- proton dissociation (N* nucleon resonances, etc.)
- Summary

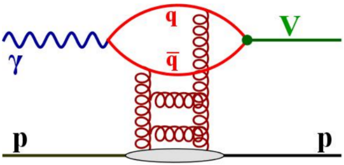
# HERA and ZEUS: 1992 – 2007, DESY, Hamburg

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

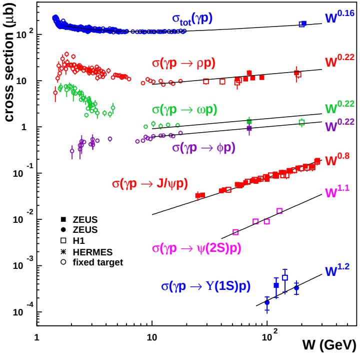



ZEUS: multipurpose, hermetic detector (MVD, CTD, CAL, F/B/RMUON, BAC, ...)
Total luminosity: $\int \mathcal{L} \sim \mathbf{500\ pb^{-1}}$ collected during HERA I + II running periods

- **Physics Motivation**

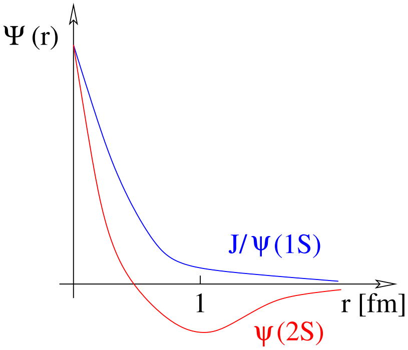



- process driven by gluons
- $\sigma \propto [xg(x, \mu^2)]^2$
- $\mathbf{x} = \mu^2/\mathbf{W}^2$ : high $W \to$ small $x$
- $\mu^2 \propto (Q^2 + M_V^2)$




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

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

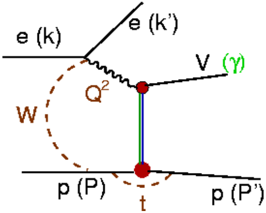


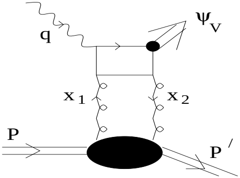

$$\text{Ratio } R = \frac{\sigma_{\gamma p \to \psi(2S)p}}{\sigma_{\gamma p \to J/\psi(1S)p}}$$

- sensitive to radial wave function of charmonium
- provides insight into the dynamics of the hard process
- (some systematics cancel out)

- $J/\psi(1S)$ and $\psi(2S)$ have the same quark composition but distinctive wave functions
- $\psi(2S)$ has a node at $\approx 0.4$ fm
- $\langle r^2_{\psi(2S)} \rangle \approx 2 \langle r^2_{J/\psi(1S)} \rangle$
- 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** $J/\psi$ **production**
- (Both Vector Mesons masses are much smaller then the $\gamma p$ center-of-mass energy)

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




Exclusive process: proton stays intact

Proton dissociation also possible → background

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

$M_V^2$ - vector meson mass squared

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

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

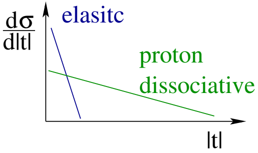
$W = (q + P)^2$ - invariant mass of the $\gamma p$ system

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

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

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

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




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

# Data selection

- **DATA sample**
- (selection of exclusive di-muon events)

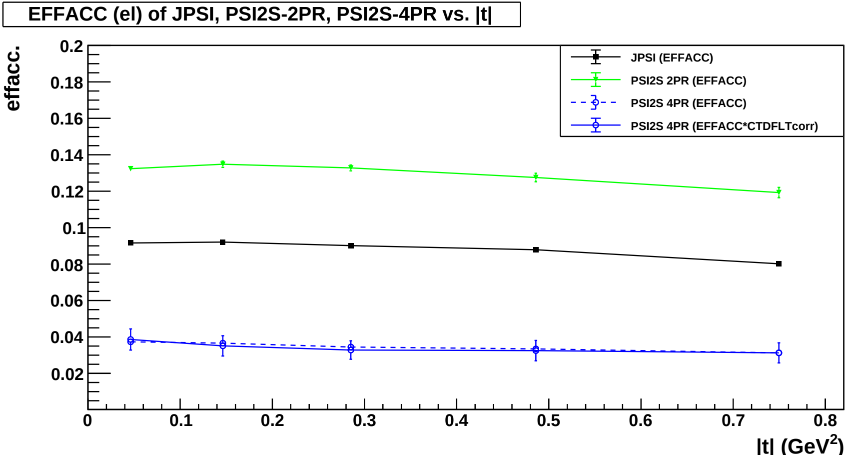
# Event Selection: 2-prongs sample: $J/\psi$, $\psi(2S) \rightarrow \mu^+\mu^-$

- 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
  - $E_{\mathrm{clu}} < 0.5$ GeV for clusters not matched to muons (or pions)
    (corresponds to an effective cut on $Q^2 < 1$ GeV$^2$)
  - $E(\theta < 0.12 rad) < 1$ 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$^2$)

# Event Selection: 4-prongs sample: $\psi(2S) \to \mu^+\mu^-\pi^+\pi^-$

- (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 ($J/\psi$ window)
- $M(\mu^+\mu^-\pi^+\pi^-) - M(\mu^+\mu^-)$ in $(0.5 - 0.7)$ GeV window
  (**cascade decay of** $\psi(2S)$)

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




- JPSI, PSI2S 2- and 4-prong (**4 ÷ 14%**)
- Higher di-muon acceptance for higher mass state (PSI2S)
- flat in $|t|$ (no angular correlations to $|t|$)
- dashed line after CTD FLT corrections

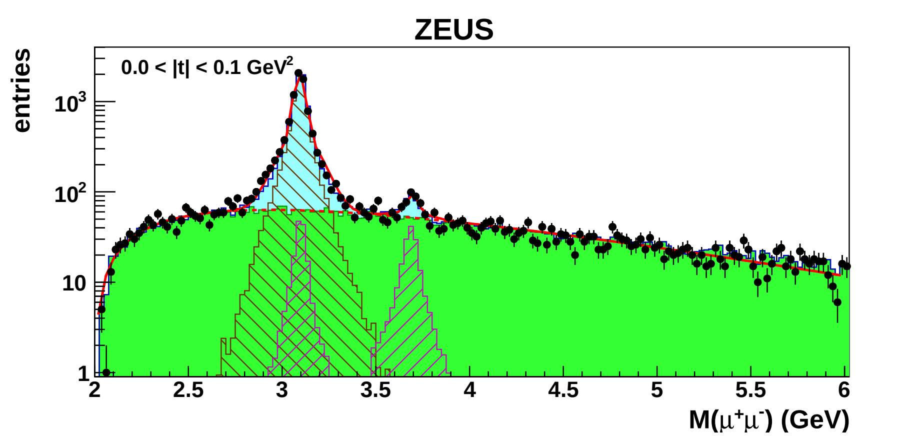
# 2-prongs: Signal extraction: fit parameterization

- 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, $\Delta$ – mass bin width,
  $m$ – mean value, $\sigma$ – RMS
- for $J/\psi$: $N_1 \cdot G_1(x) + N_2 \cdot G_2(x)$
- for $\psi'$: $N'_1 \cdot g_1(x) + N'_2 \cdot g_2(x)$
- introducing: $N = N_1 + N_2$, $N' = N'_1 + N'_2$, $R = \frac{N'}{N}$
- with additional constrains: $m_1 = m_2$, $m'_1 = m'_2$,
  $\frac{\sigma'_1}{\sigma_1} = \frac{\sigma'_2}{\sigma_2} = \alpha$, $\xi = \frac{N_1}{N} = \frac{N'_1}{N'}$ (**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 $(= 2p^{\mu}_{t,min})$

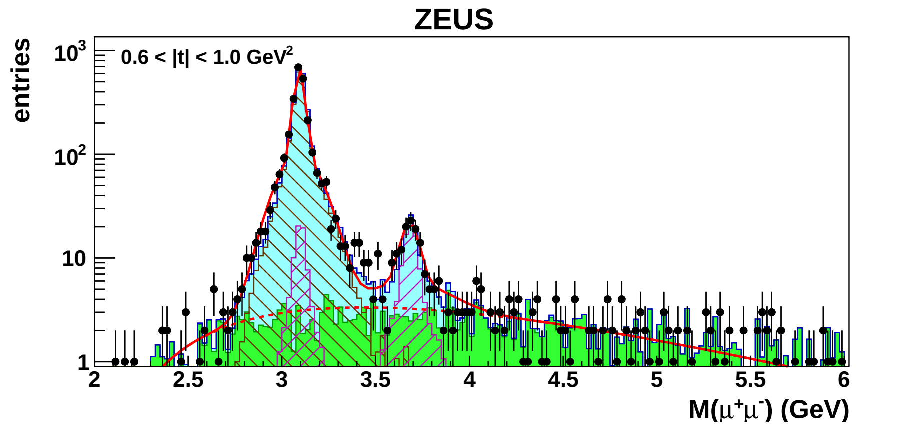
### $M(\mu^+\mu^-)$




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

# 2-prongs: dimuon mass spectra

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




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

- **Cross section ratio**

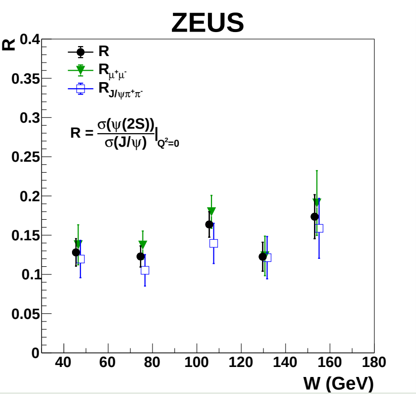
# Cross section ratio $R = \frac{\sigma(\psi(2S))}{\sigma(J/\psi(1S))}$, full kinematic range

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

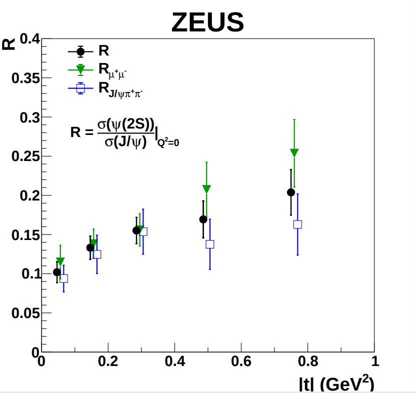
| $\psi(2S)$ decay mode | $R = \frac{\sigma(\psi(2S))}{\sigma(J/\psi(1S))}$ |
|---|---|
| $\mu^+\mu^-$ | $0.154 \pm 0.012$ |
| $J/\psi(\to \mu^+\mu^-)\pi^+\pi^-$ | $0.125 \pm 0.019$ |
| combined | $0.146 \pm 0.010^{+0.016}_{-0.020}$ |

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

## $R$ vs. $W$

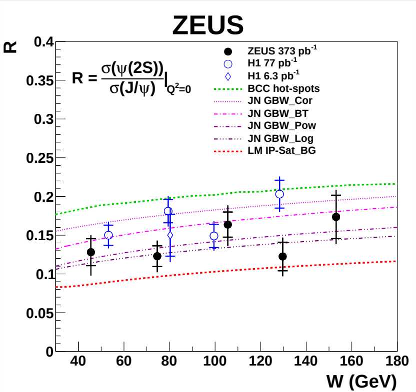



## $R$ vs. $|t|$

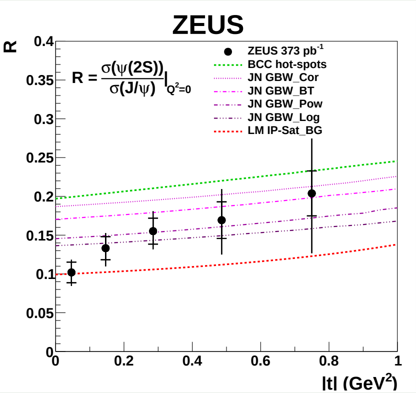



- $R_{\mu\mu}$ (2-prongs channel), $R_{J/\psi\pi\pi}$ (4-prongs channel) and combined $R$ (full dots)
- statistical errors only
- **good agreement between two channels**

## $R$ vs. $W$



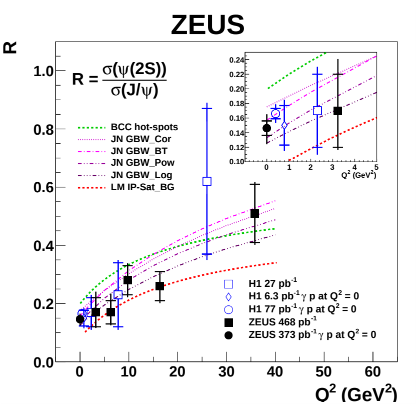

## $R$ vs. $|t|$




- 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. $Q^2$




## 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 (→ backup plots, page **??**)
- better precision of photoproduction points

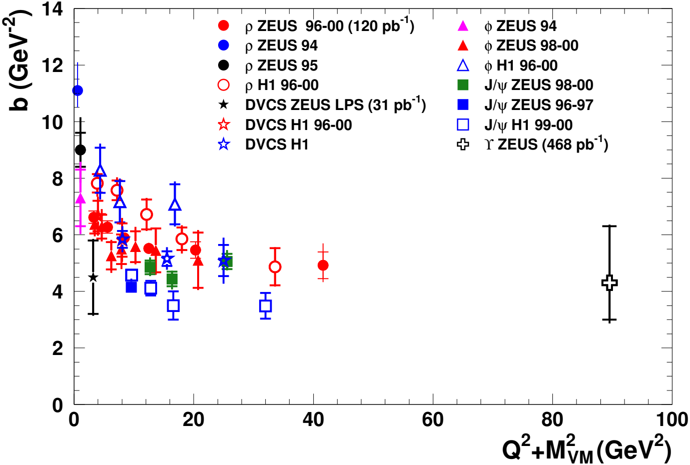
# Tuning of signal MC

- **Tuning of** DIFFVM **Monte Carlo**

# Tuning of DIFFVM MC sample

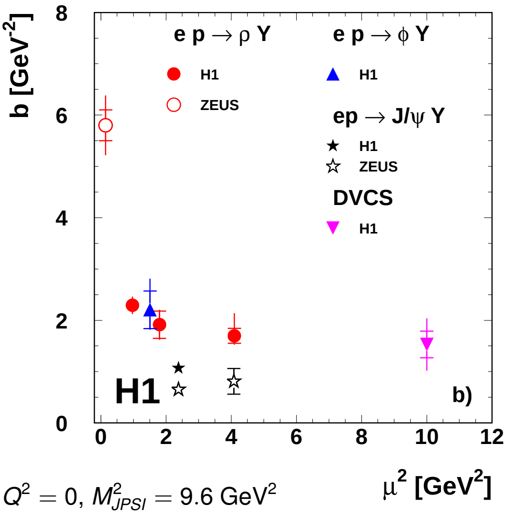
- Reweighting of MC sample at generator level
- $|t|$ dependence: $\sim \exp(-b|t|)$, generated with $b_{el} = 4.0$, $b_{pd} = 1.0$
  reweighted to:
  $b_{el} = 4.6 \pm 0.3$, $b_{pd} = 1.0 \pm 0.1$ (JPSI)
  $b_{el} = 4.3 \pm 0.7$, $b_{pd} = 0.7 \pm 0.2$ (PSI2S)
- shrinkage added by reweighting: $b = b_0 + 4.0\alpha' \log(W/W_0)$;
  $\alpha' = 0.12 \pm 0.04$ 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**

# Summary of elastic *b*-slopes



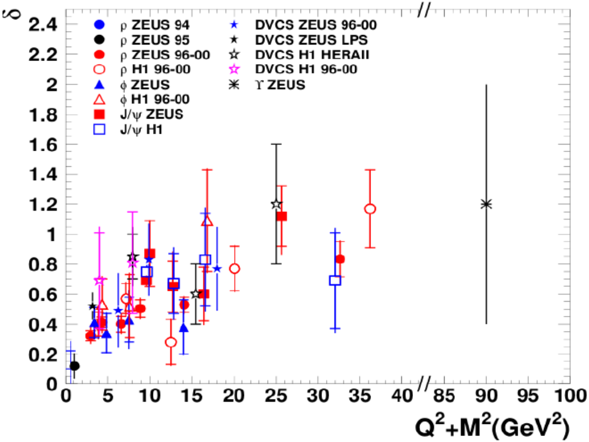

- PHP: $Q^2 = 0$, $M^2_{JPSI} = 9.6$ GeV$^2$
- significant difference for different measurements...

# Summary of p.diss *b*-slopes




- PHP: $Q^2 = 0$, $M^2_{JPSI} = 9.6$ GeV$^2$
- for $J/\psi$ : $b_{pd} \sim 1.0$ GeV$^{-2}$

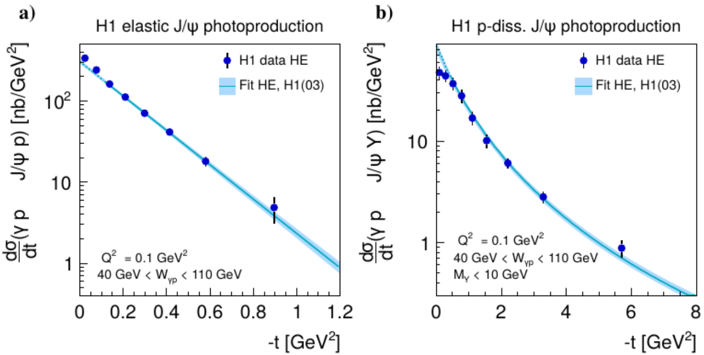
# Summary of elastic $\delta$-powers




- PHP: $Q^2 = 0$, $M^2_{JPSI} = 9.6$ GeV$^2$
- significant difference for different measurements...

- **Extracting of the model parameters**
- (example for the $t$-spectra slopes)

# Example $t$-spectra: H1 results




- (Eur. Phys. J. **C 73** (2013), 2466 )
- two **features common for many exclusive VM analyses**:
- excess of elastic events for very small $|t|$
  (BH background ? p.diss BG for low $M_Y$ - steeper $b$-slope ?)
- deficit of p-diss. events for very small $|t|$ (threshold effect ?)

- **elastic $t$-slope:** $\sim \exp\left(-b_{el}|t|\right)$
- **H1:** (HERA-II JPSI paper) : $b_{el} = 4.88 \pm 0.15\ \text{GeV}^{-2}$
  (Eur. Phys. J. **C 73** (2013), 2466 )
- **H1:** (HERA-I PSI2S paper) : $b_{el} = 4.99 \pm 0.13 \pm 0.39\ \text{GeV}^{-2}$
  (Phys. Lett. **B 541** (2002), 251-264)
- **ZEUS:** (HERA-I JPSI paper) : $b_{el} = 4.15 \pm 0.05^{+0.30}_{-0.18}\ \text{GeV}^{-2}$
  (Eur. Phys. J. **C 24** (2002) 3, 345-360)
- **some tension between ZEUS and H1 results**
- **H1:** unfolding $t$-spectra to correct for bin-to-bin migration, simultaneous fit to elastic + p.diss component
- **ZEUS:** single $\exp()$ fit to uncorrected data but sophisticated p.diss subtraction
- (this analysis : $b_{el} = 4.6 \pm 0.3$ (stat. $\oplus$ syst.) GeV$^{-2}$)

# JPSI elastic $|t|$-slopes $b_{el}$ : ZEUS HERA-I analysis

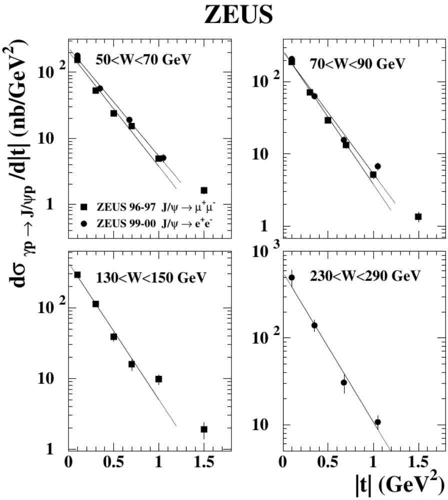
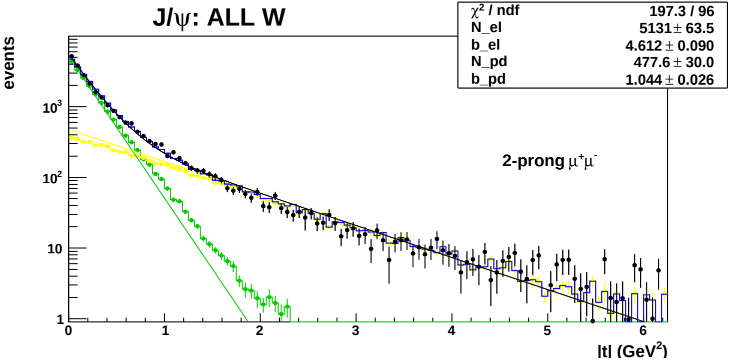



**Figure 6:** *The differential cross-section $d\sigma_{\gamma p \to J/\psi p}/dt$ for exclusive $J/\psi$ photoproduction for representative bins of $W$ and for the decay channels, $J/\psi \to \mu^+\mu^-$ (squares) and $J/\psi \to e^+e^-$ (points). The vertical bars indicate the statistical uncertainties only. The full lines represent the results of a fit of the form $d\sigma/dt = d\sigma/dt|_{t=0} \cdot e^{bt}$ performed in the range $-t < 1.2\ GeV^2$ for the muon channel and in the range $-t < 1.25\ GeV^2$ for the electron channel.*

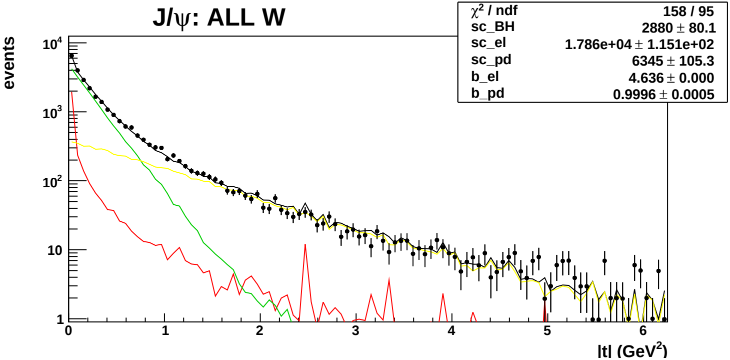
- single $\exp()$ fits for $|t| < 1.2$ GeV$^2$
- p.diss dominates for $|t| >\sim 1.0$ GeV$^2$

# $t$-spectra analytical fit: JPSI di-muon mass window




- Green: elastic, Yellow: p.diss components
- double exp() fit to uncorrected data (MC superimposed on top of the fit)
- **Bethe-Heitler background subtracted** (via MC templates)
- $b_{el} = 4.6 \pm 0.1$ (stat.), $b_{pd} = 1.0 \pm 0.03$ (stat.)
- some smearing visible for MC on detector level (see next pages)

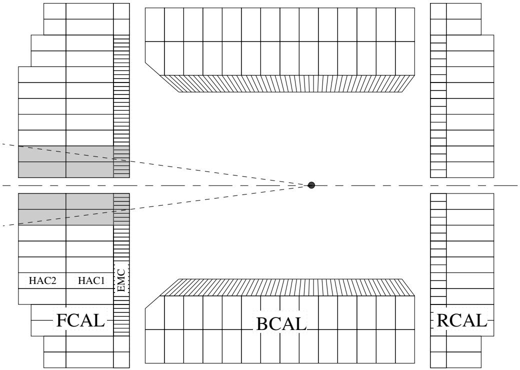
# another approach: $t$-spectra template fit

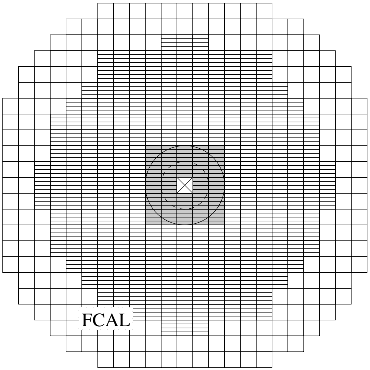



- **triple MC template fit to uncorrected data**
- simultaneous fit of **BH**+**el**+**p.diss** components
- both $b$-slopes reweighted on generator "true" level
- $b_{el} = 4.6$, $b_{pd} = 1.0$ (problems with MINUIT errors, limited MC statistic)
- smearing and other "detector/cuts" effect included in templates

- **extracting fractions of proton dissociation**

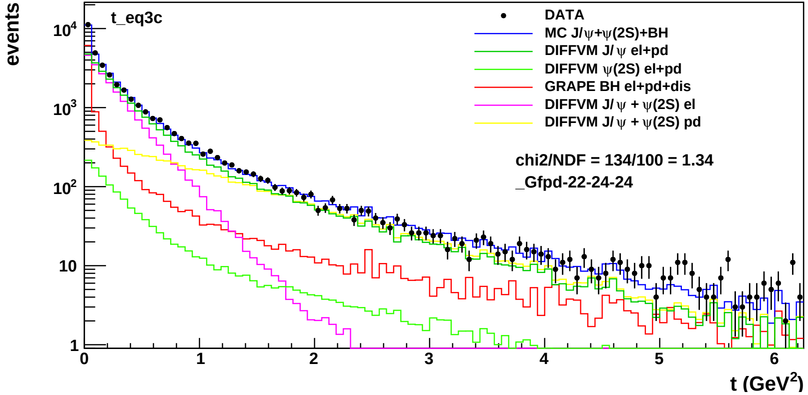
# Proton dissociation taggers



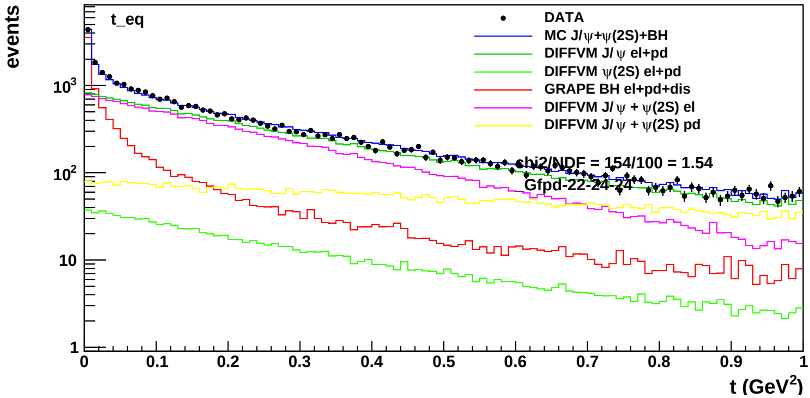




- Energy in forward cone to suppress p.diss events: $\theta_{max} = 0.12\ rad$
- using EFO : "Energy Flow Objects" (trackers + CAL info):

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

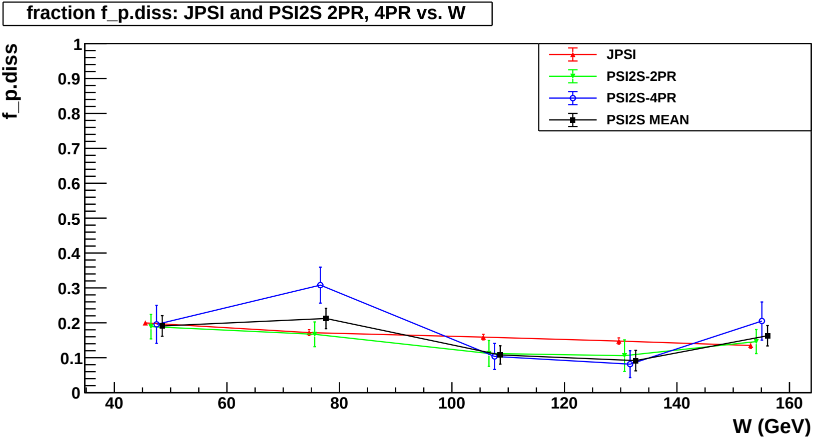



- **spectra like this are** used to evaluate the p.diss fractions (use longer "lever arm" then integrate it up to $|t| = 1.0$ GeV$^2$)
- using root package `TFractionalFitter`
- fitted $f_{p.diss} = 0.22$ and $= 0.24$ (JPSI and PSI2S, BH subtracted)
- **p.diss take over elastic around** $\sim$ **1 GeV**$^2$ (yellow and magenta histos)



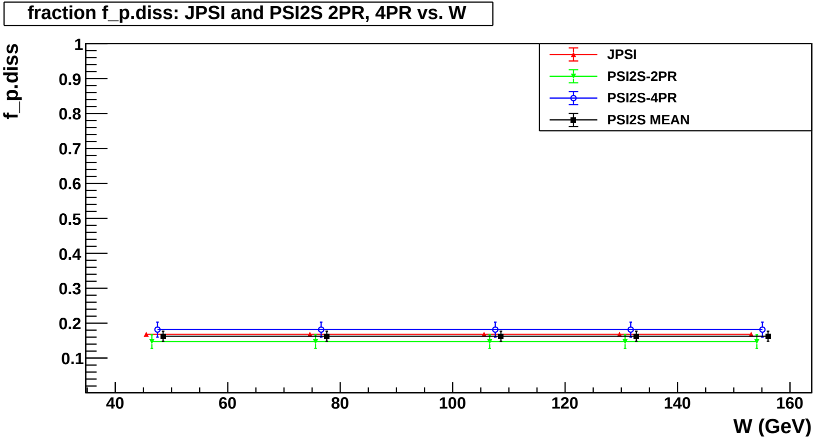

- zoom for $|t| < 1$ GeV$^2$
- fitted $f_{p.diss} = 0.22$ and $= 0.24$ (JPSI and PSI2S, BH subtracted)
- $b_{el} = 4.6$ GeV$^{-2}$, $b_{pd} = 1.0$ GeV$^{-2}$ (JPSI)
- $b_{el} = 4.3$ GeV$^{-2}$, $b_{pd} = 0.7$ GeV$^{-2}$ (PSI2S)
- good MC modeling of the spectra is crucial !

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



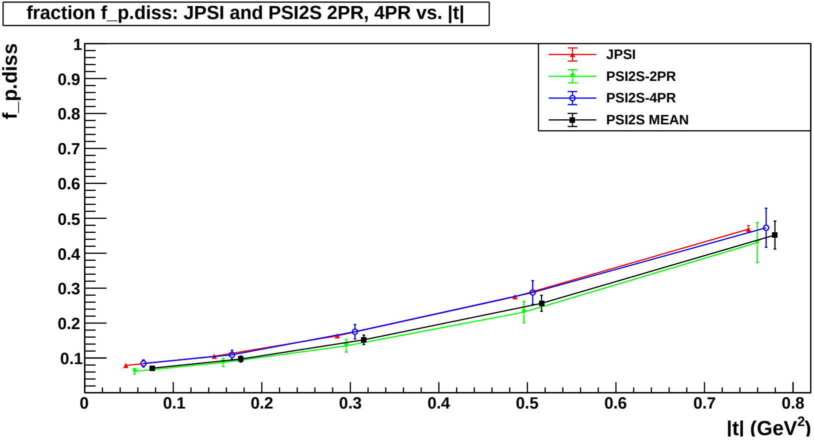

- average value ∼ 17% JPSI and ∼ 16% PSI2S (mean)
- compatible results for 2- and 4-prong channels, no *W* dependence
- **black**: weighted mean for PSI2S 2- and 4-prong
- bigger fluctuations for PSI2S 2- and 4-prongs

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



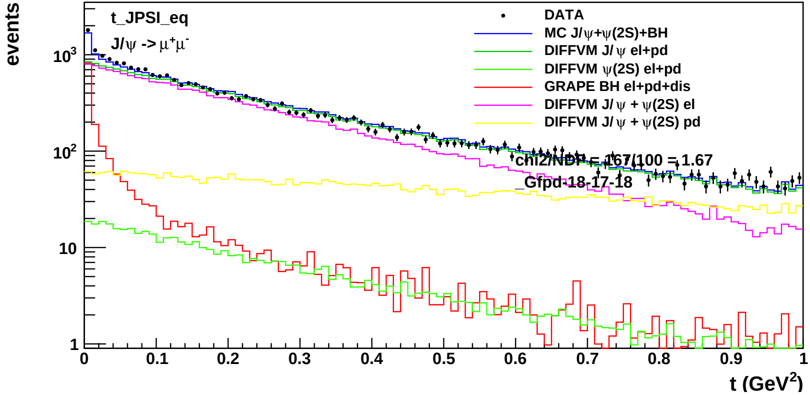

- average value $\sim$ 17% JPSI and $\sim$ 16% PSI2S (mean)
- **black**: weighted mean for PSI2S 2- and 4-prong (used in analysis)
- for R analysis: the same mean value is used for all $W$ bins
- no significant impact on final ratio $R$ ($f_{p.diss}$ fractions cancels out)

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

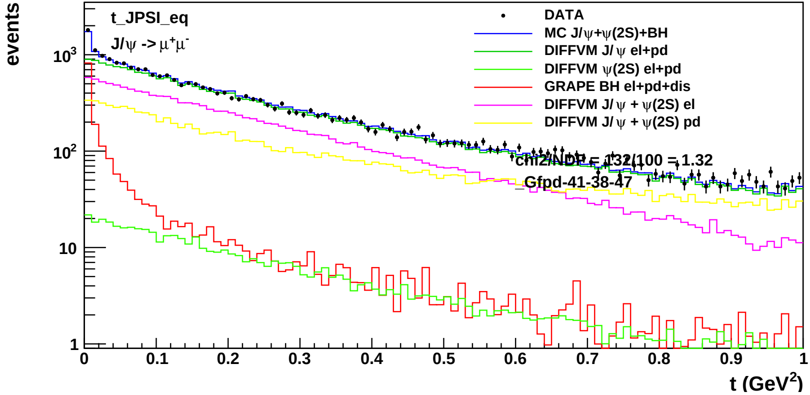



- compatible results for 2- and 4-prong channels
- **black**: weighted mean for PSI2S 2- and 4-prong (used in analysis)
- negligible effect on final R analysis ($f_{p.diss}$ fractions cancels out)
- bigger impact on systematics for large $|t|$ due to the *b*-slope variation !

# Comparison with two exp() model (zoom for $|t| < 1.0$ GeV$^2$)




- “standard” two components model: single exp() for elastic and p.diss
- yellow : p.diss with $b_{pd} = 1.0$ GeV$^{-2}$
- some indication for excess of events at very low $|t| < 0.1$ GeV$^2$ (?)
- **could be imperfect description of BH background as well...**
- $f_{p.diss} = 18\%$ ($|t| < 1$ GeV$^2$)

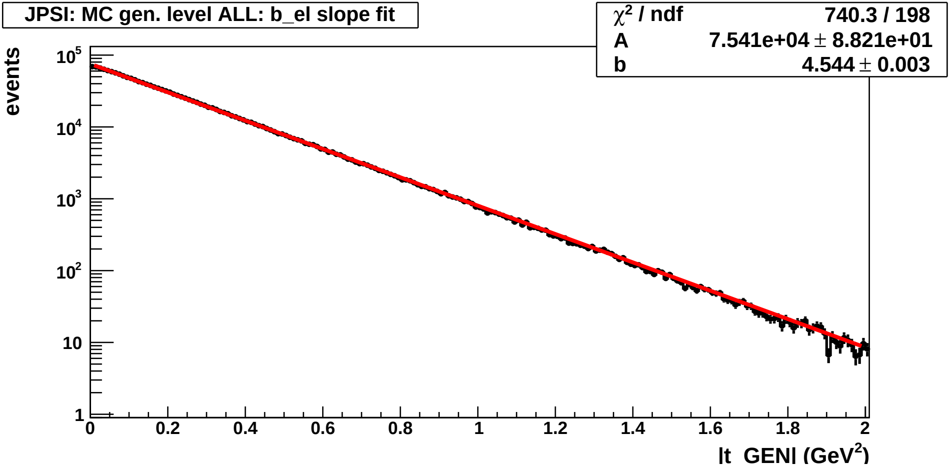



- reweighting the resonances $M_Y < 1.9$ GeV to $b_{pd-loMY} = 6.5$ GeV$^{-2}$ (yellow histogram)
- a bit better agreement in terms of $\chi^2$ ...
- $f_{p.diss} = 41\%$ ($|t| < 1$ GeV$^2$) !?
- which scenario is realized by Nature ?
- $\rightarrow$ selection of clean p.diss, low $M_Y$ events needed (incl. triggering on low $M_Y$)

# MC DIFFVM generator level

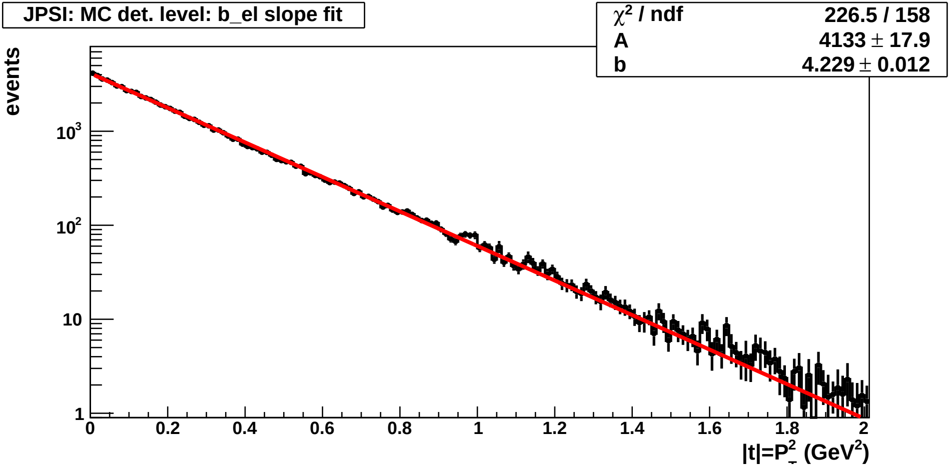
- **MC exercise:** generator level $\rightarrow$ detector level
- elastic and p.diss $t$-spectra

# elastic JPSI: MC DIFFVM generator level



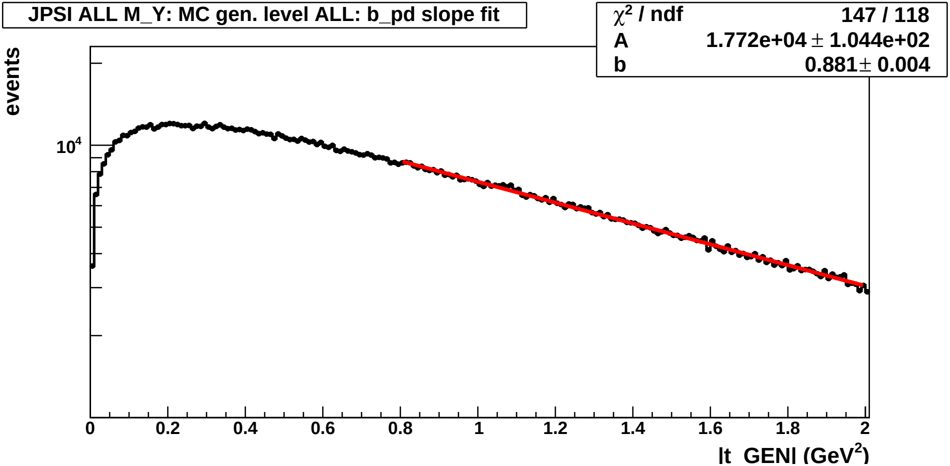

- elastic JPSI: generator level "true" $|t|$-distribution before cuts, (calculated using gen-level 4-vectors including scattered $e'$)
- reweighted to: $b_{el} = 4.6\ \mathrm{GeV}^{-2}$ (realistic example)

# elastic JPSI: MC DIFFVM detector level




- elastic JPSI: detector level $|t|$-distribution **after selection cuts**, **smearing** due to the finite resolution (bin to bin migration), calculated using **approximate formulae** $|t| \approx p^2_{T,VM}$
- systematic shift in the $t$-slope from 4.6 to 4.2 $\text{GeV}^{-2}$

# p.diss JPSI: MC DIFFVM generator level




- p.diss *t*-distribution is non-exponential already at generator level !
- kinematical threshold effect
  (minimal 4-momentum transfer needed to excite/break-up the proton)

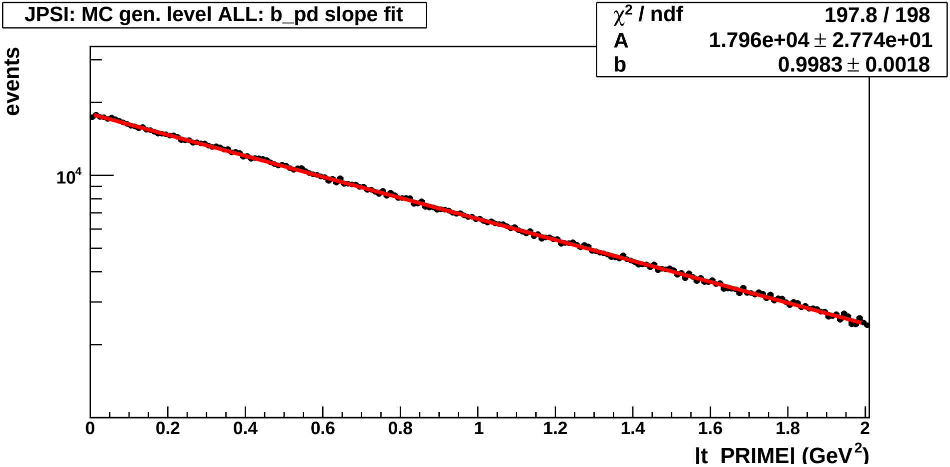
- $t'$ variable corrected for threshold effect:

```
amprot = PMASS;
mdiff  = M_Y_gen;
q2g    = Q2_gen;
mppg   = mass_VM_gen;
Wg     = W_gen;

t_min = ((amprot*amprot-mdiff*mdiff+q2g+mppg*mppg)/(2*Wg))*
         ((amprot*amprot-mdiff*mdiff+q2g+mppg*mppg)/(2*Wg))
        -(sqrt(((Wg*Wg + amprot*amprot+q2g)/(2*Wg))*
         ((Wg*Wg + amprot*amprot+q2g)/(2*Wg))-amprot*amprot)
        -sqrt(((Wg*Wg+mdiff*mdiff-mppg*mppg)/(2*Wg))*
         ((Wg*Wg+mdiff*mdiff-mppg*mppg)/(2*Wg))-mdiff*mdiff))*
         (sqrt(((Wg*Wg + amprot*amprot+q2g)/(2*Wg))*
         ((Wg*Wg + amprot*amprot+q2g)/(2*Wg))-amprot*amprot)
        -sqrt(((Wg*Wg+mdiff*mdiff-mppg*mppg)/(2*Wg))*
         ((Wg*Wg+mdiff*mdiff-mppg*mppg)/(2*Wg))-mdiff*mdiff));

t_prime = t_gen - abs(t_min);
```

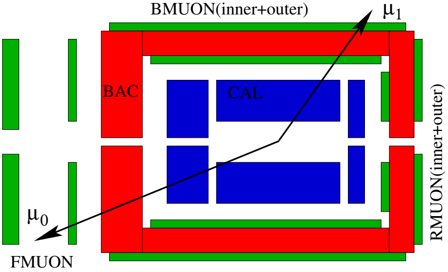
# p.diss JPSI: MC DIFFVM generator level




- **p.diss $t'$-distribution is exponential**
- reweight p.diss MC using $t'$ !
- correct fitted $b_{el}$ slope for detector level bias

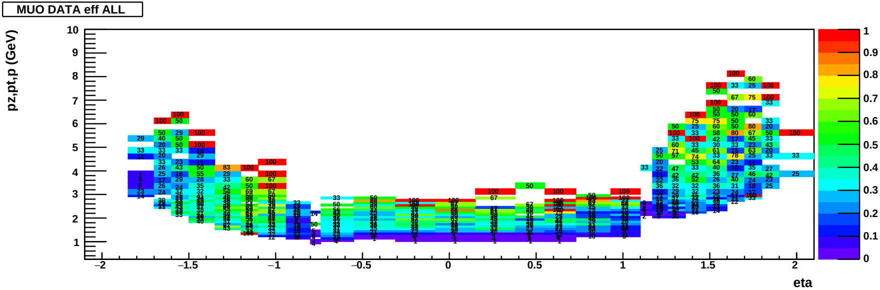
# Muon effic. corrections: TAG and PROBE

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



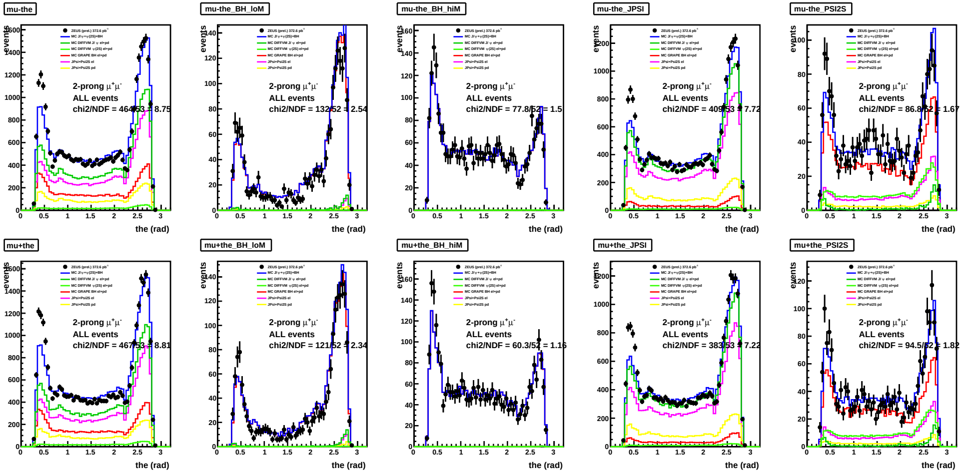

- one step correction for (FLT and SLT and TLT and off-line REC)
- separate maps for F/B/R/MUO, BAC and CAL (off-line only)
- evaluated for single muon in $(pt_{eff}, \eta)$ bins, where as $pt_{eff}$ is used:
  (motivated by the CAL/BAC geometry and scaling of the muon path length)
  - $p$ in Forecap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

# Muon correction maps: ($p_z, p_t, p$ *vs.* $\eta$) - DATA



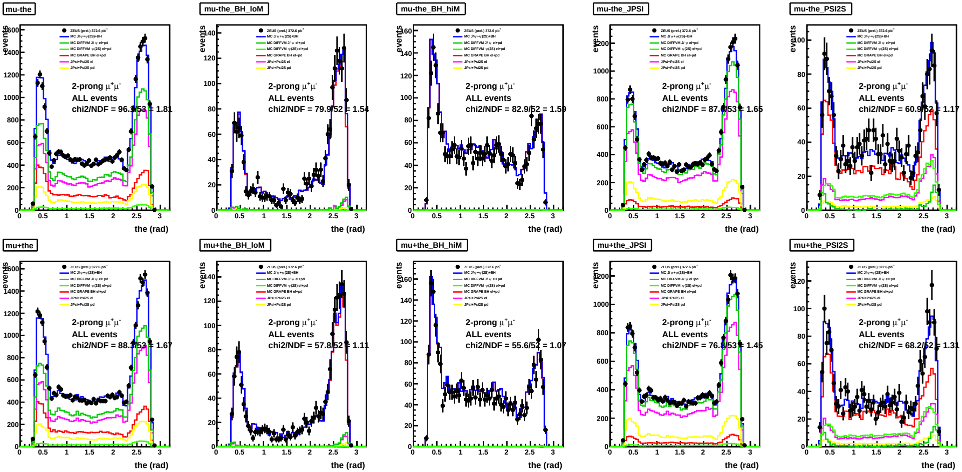

- **muon tomography**
- probability (%) to fire FLT-SLT-TLT-REC chain by single muon on $(p_z, p_t, p; \eta)$ grid
- X-axis (along eta): Rear-MUO, Barrel-MUO, Forward-MUO detectors
- only events with $M(\mu^+, \mu^-) < 6$ GeV
  (ie. in the phase space range of di-muon mass fits)
- current choice for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

# 2-prongs: before muon corrections: $\theta_{\mu\pm}$ in mass bins




- top: $\theta_{\mu-}$, bottom: $\theta_{\mu+}$
- ALL events, BH-loM, BH-hiM, $J/\psi$ peak, $\psi'$ peak
- standard (production version) of detector MC: “as it is”
- MC deficit in forward direction or MC over-efficient in rear

# 2-prongs: after muon corrections: $\theta_{\mu^\pm}$ in mass bins




- ALL events, BH-loM, BH-hiM, $J/\psi$ peak, $\psi'$ peak
- good agreement in all mass windows (validation of muon corrections)
- (different processes, different $\mu^\pm$ angular/momentum distributions, different boost)