Lessons learned from exclusive J/ψ and $\psi(2S)$ production at HERA

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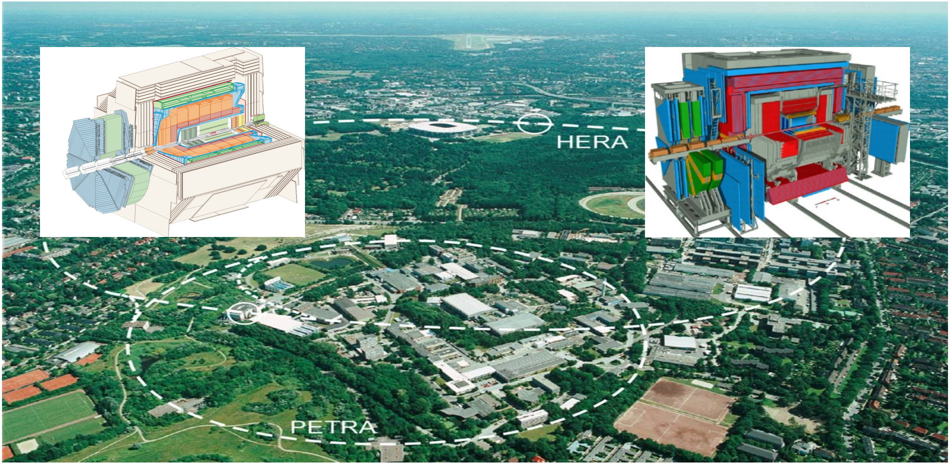
Physics Opportunities with Heavy Quarkonia at the EIC, (online), 25 – 27 October 2021

- HERA accelerator, H1 and ZEUS experiments
- case study based on ongoing analysis
  (J/ψ to $\psi(2S)$ cross section ratio in exclusive photoproduction, $\mu^+\mu^-$ channel)
- DIS vs. PHP (trigger strategy)
- **Data sample, signal and background**
- Monte Carlo, tuning of parameters,
  controlling efficiency/acceptance corrections
- extracting *t*-slopes from data
- proton dissociation (N* nucleon resonances)
- forward energy flow (forward taggers)
- Summary/Conclusions

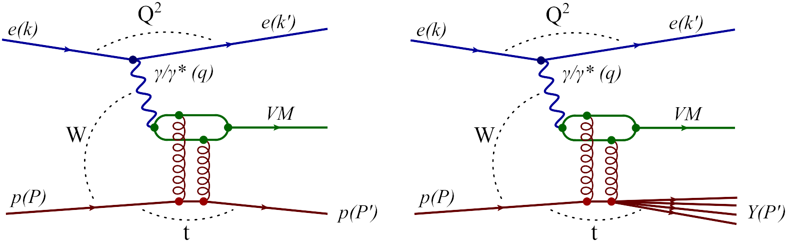
The HERA Accelerator, 1992 – 2007, DESY, Hamburg

World's first and only (so far...) $e^{\pm}p$ collider, $\mathbf{E_e = 27.5}$ **GeV**, $\mathbf{E_p = 920}$ **GeV**



Total luminosity: $\int \mathcal{L} \sim$ **500 pb^{-1}** collected per H1 and ZEUS experiments (HERA I + II running periods)

Kinematics of exclusive and p.diss VM production



- $ep \to e + VM + p$, elastic process, $VM = J/\psi(1S)$ or $\psi(2S)$
- $ep \to e + VM + Y$, proton dissociative process
- k, k', P, P', 4-momenta of the incoming and outgoing e and p
- $W^2 = (q + P)^2 = -Q^2 + 2y(k \cdot P) + m_p^2$, $W \approx \sqrt{2E_P(E - P_Z)}$,
- $t = (P - P')^2 \approx -p_{t,VM}^2$,
- $Q^2 = -q^2 = -(k - k')^2$,
- M_{VM}, M_Y
- in red are detector level quantities, if scattered electron not measured

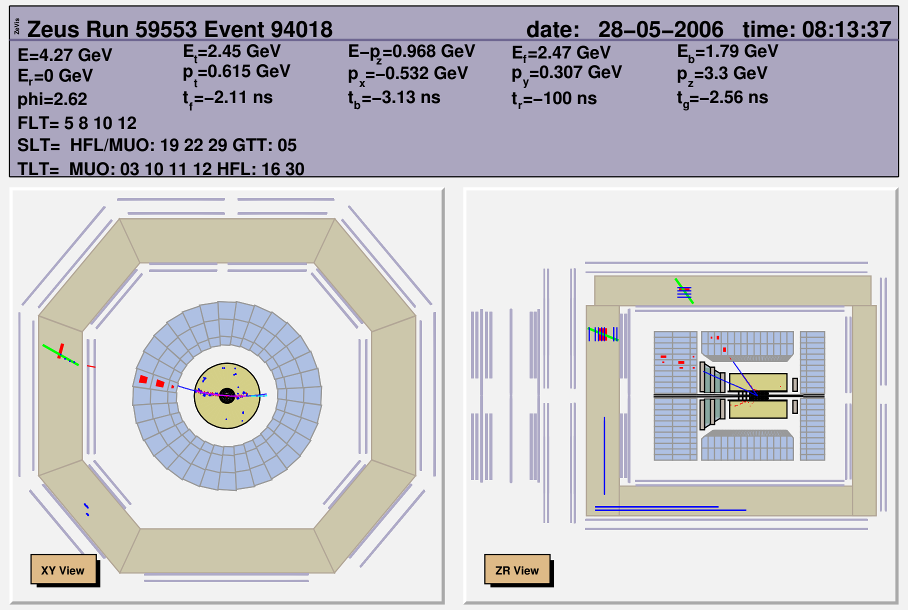
DIS (electroproduction) vs. photoproduction (γp) of exclusive J/ψ

- **Large fraction of cross section located at low-Q^2 !**
- $\sigma(ep \rightarrow J/\psi + p) \sim 1000$ pb at $W \approx 100$ GeV and $Q^2 \approx 0$ GeV^2
- (about 100 000 pb for γp cross section due to photon flux factor)

- $\sigma(ep \rightarrow J/\psi + p) \sim 300$ pb at $W \approx 100$ GeV and $Q^2 \approx 0.4$ GeV^2
- $\sigma(ep \rightarrow J/\psi + p) \sim 35$ pb at $W \approx 100$ GeV and $Q^2 \approx 3.0$ GeV^2
- $\sigma(ep \rightarrow J/\psi + p) \sim 15$ pb at $W \approx 100$ GeV and $Q^2 \approx 7.0$ GeV^2
- $\sigma(ep \rightarrow J/\psi + p) \sim 8$ pb at $W \approx 100$ GeV and $Q^2 \approx 16.0$ GeV^2
- (ZEUS: Nucl. Phys. **B 695**, 3-37,2004)
- steep Q^2 dependence, cross section drops fast with Q^2
- DIS: clean, efficient **trigger from scattered electron** (e')
- PHP: requires **triggering on VM decay products**

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

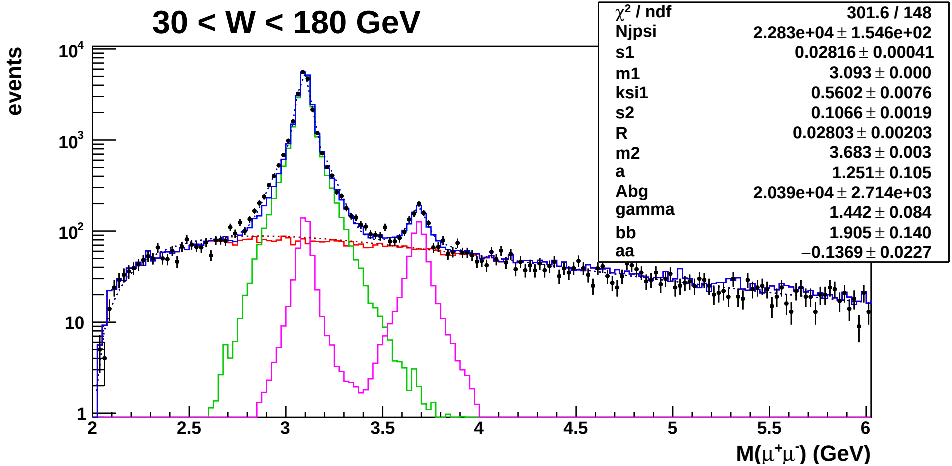
Example of exclusive di-muon topology in PHP



2-prongs: main selection cuts

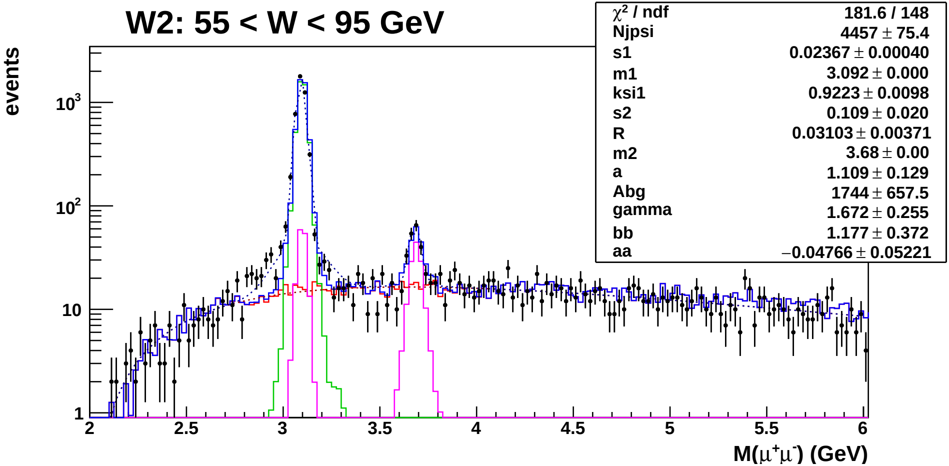
- (2-prongs: J/ψ, $\psi(2S) \to \mu^+\mu^-$)
- all exclusive muon trigger slots
- $N_{trk} = 2$, both tracks from primary vertex, opposite charge
- PHP: reject events with scattered e' in CAL ($E_e > 5$ GeV)
- elasticity cut on EFOs: (Energy Flow Objects)
  no EFO unmatched to muon track with $E^{CAL}_{ZUFO} > 0.5$ GeV (CAL uranium noises)
- anti-p.diss cut: $E(\theta < 0.12) < 1.0$ GeV
  (Forward Energy Flow)
- muon identification in at least one muon detector
  both muons identified by CAL MIP finder
- muon tracks $p_T^{\mu} > 1.0$ GeV
- $30 < W < 180$ GeV $\to$ acceptance of muon detectors and tracker $\eta \in (-2, 2)$
- $|t| < 1.0$ GeV $\to$ to further suppress p.diss events

DATA SEMPLE: Di-muon mass spectrum $M(\mu^+\mu^-)$



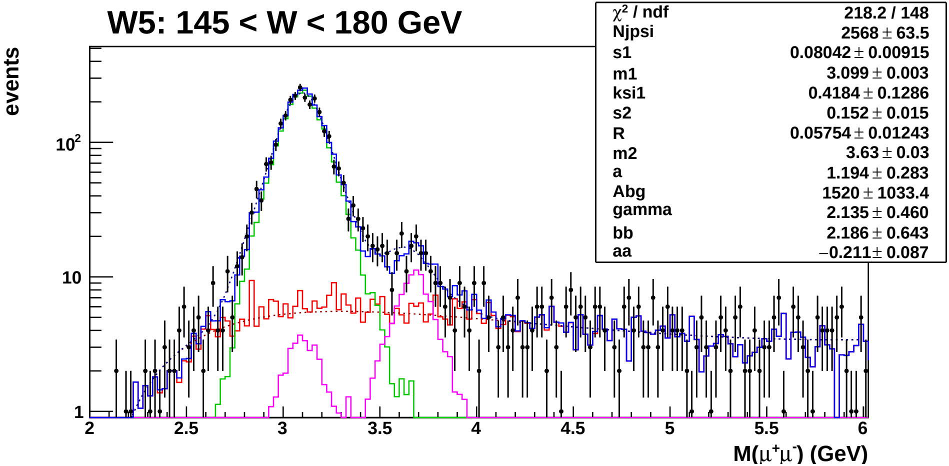
- good **double Gaussian** fits and DATA/MC agreement for all W and $|t|$ bins
- resonant background to J/ψ peak from cascade decays:
  $\psi(2S) \rightarrow J/\psi + \pi^+\pi^-$
  $\psi(2S) \rightarrow J/\psi + \pi^0\pi^0$ and $\chi_{0,1,2}$ with gammas decays

Di-muon mass $M(\mu^+\mu^-)$ (intermediate W)



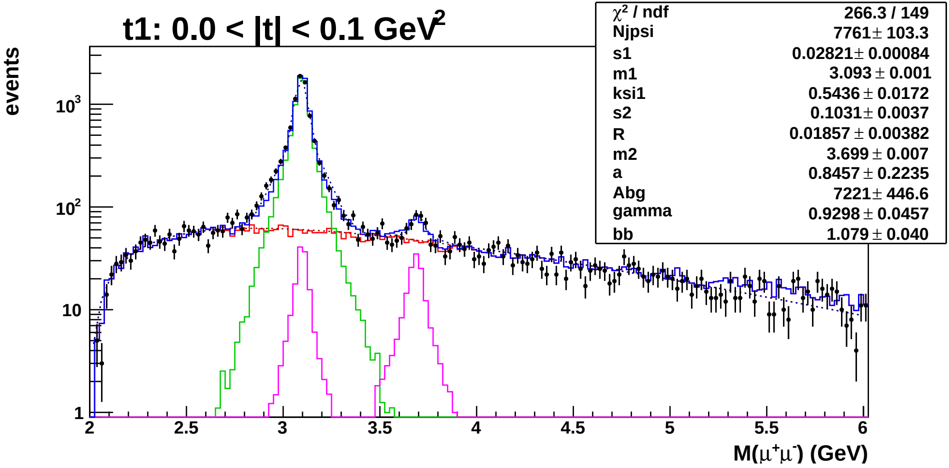
- best mass resolution: central rapidity (barrel), long tracks
- tail of J/ψ peak: some indication of radiation effects (?)
  (not included in DIFFVM MC, more important for e^+e^- channel)

Di-muon mass $M(\mu^+\mu^-)$ (high W)



- rear tracks, poor mass resolution
- significant migration between resonant peaks
- to access low/high W good tracking in forward/rear direction is needed !

Di-muon mass $M(\mu^+\mu^-)$ (very small t)



- low $|t|$, bin dominated by BH BG
- lowest signal to background (S/BG) ratio,
  $\rightarrow$ importance of good modeling of Bethe-Heitler process

- **Signal MC:** DIFFVM
- **Background MC:** GRAPE

Signal Monte Carlo: DIFFVM

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

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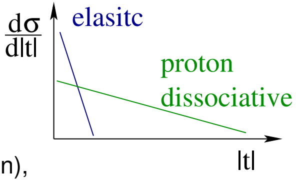
- soft diffractive processes in the Regge framework and Vector Dominance Model
- $\frac{d\sigma}{dQ^2} \propto \frac{1}{(1+Q^2/M_V^2)^{1.5}}$
- $\frac{d\sigma}{d|t|} \propto W_{\gamma p}^{4\epsilon} e^{-b|t|}$ $(4\epsilon = \delta)$ (elastic)
- $\frac{d^2\sigma}{d|t|dM_Y^2} \propto W_{\gamma p}^{4\epsilon} e^{-b'|t|} M_Y^{-\beta}$ (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



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

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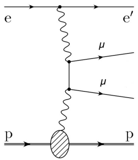
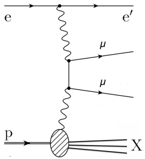
- based on the exact matrix elements in the electroweak theory at tree level via $\gamma\gamma$, γZ^0, $Z^0 Z^0$
  and via photon internal conversion (QED Compton)
- Feynman amplitudes are generated by the automatic calculation system GRACE
- **proton vertex** covers the whole kinematical region
- interface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





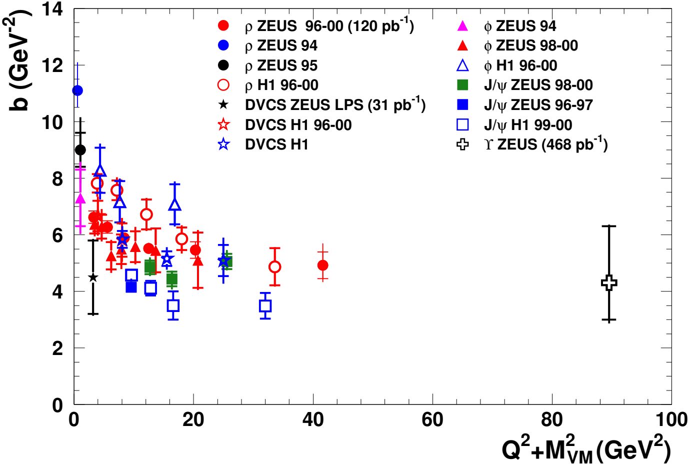
Tuning of signal MC

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

Tuning of DiffVM MC sample

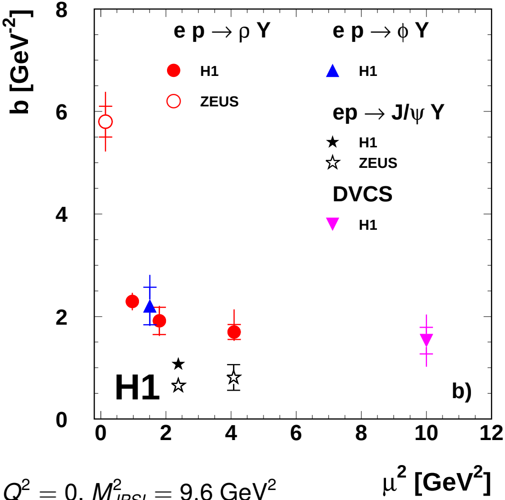
- Reweighting of MC sample at generator level
- $|t|$ dependence: $\sim \exp(-b|t|)$, generated with $b_{el} = 4.0$, $b_{pd} = 1.0$
  reweighted to:
  $b_{el} = 4.6 \pm 0.3$, $b_{pd} = 1.0 \pm 0.1$ (JPSI)
  $b_{el} = 4.3 \pm 0.7$, $b_{pd} = 0.7 \pm 0.2$ (PSI2S)
- shrinkage added by reweighting: $b =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



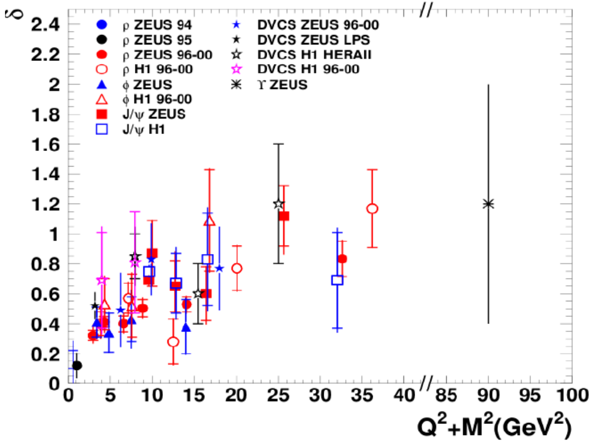
- PHP: $Q^2 = 0$, $M^2_{JPSI} = 9.6$ GeV^2
- significant difference for different measurements...

Summary of p.diss *b*-slopes



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

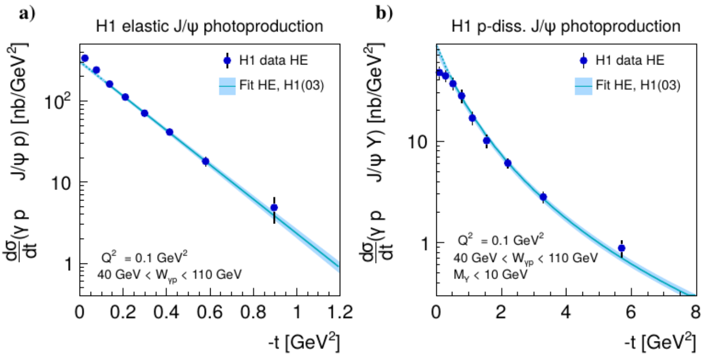
Summary of elastic δ-powers



- 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 ?)

Example: HERA JPSI elastic $|t|$-slope measurements: b_{el}

- **elastic *t*-slope:** $\sim \exp(-b_{el}|t|)$

- **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

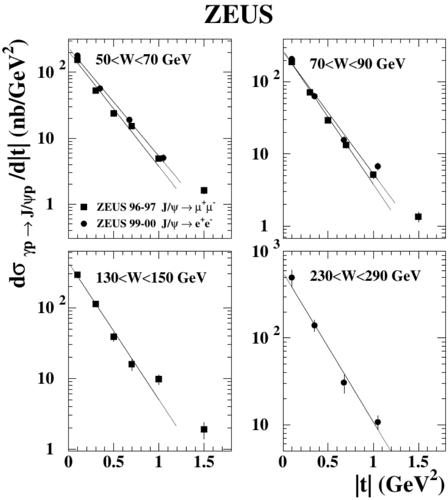
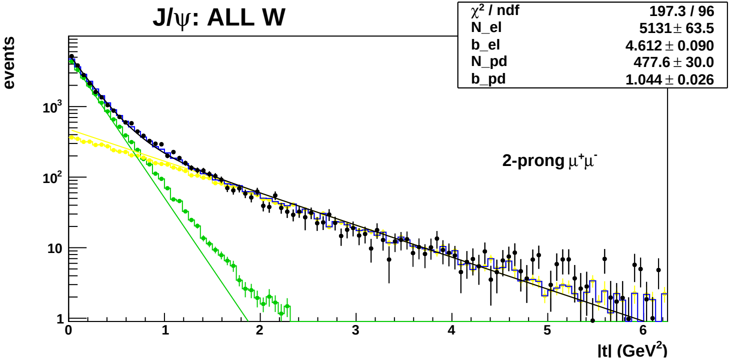


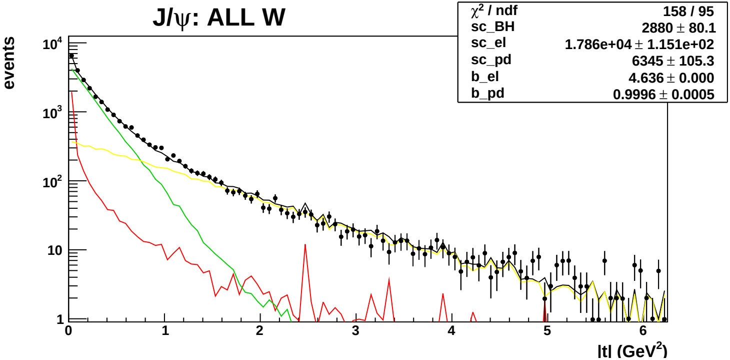
Figure 6: *The differential cross-section $d\sigma_{\gamma p \to J/\psi p}/dt$ for exclusive J/ψ photoproduction for representative bins of W and for the decay channels, $J/\psi \to \mu^+\mu^-$ (squares) and $J/\psi \to e^+e^-$ (points). The vertical bars indicate the statistical uncertainties only. 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



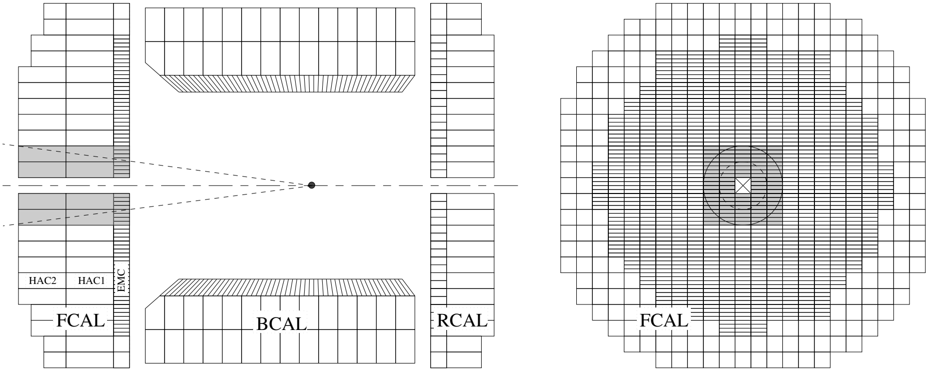
- Green: elastic, Yellow: p.diss components
- double exp() fit to uncorrected data (MC superimposed on top of the fit)
- **Bethe-Heitler background subtracted** (via MC templates)
- $b_{el} = 4.6 \pm 0.1$ (stat.), $b_{pd} = 1.0 \pm 0.03$ (stat.)
- some smearing visible for MC on detector level (see next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



- **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

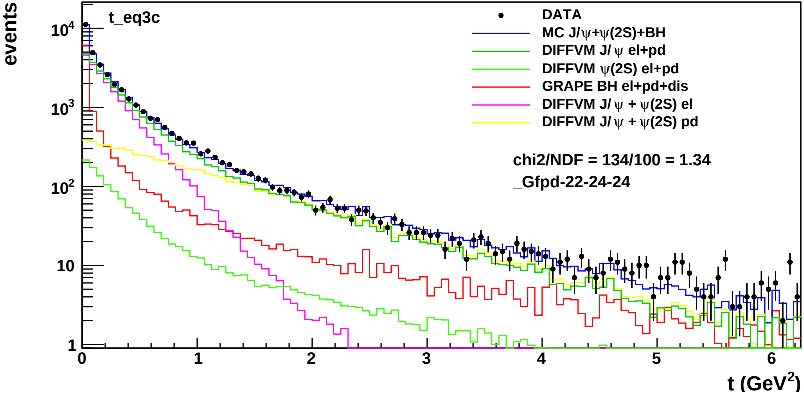
- **extracting fractions of proton dissociation**

Proton dissociation taggers

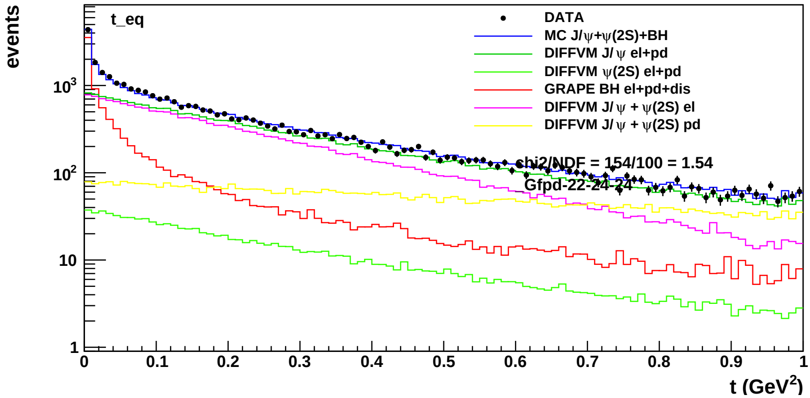


- Energy in forward cone to suppress p.diss events: $\theta_{max} = 0.12\ rad$
- using EFO : "Energy Flow Objects" (trackers + CAL info):

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



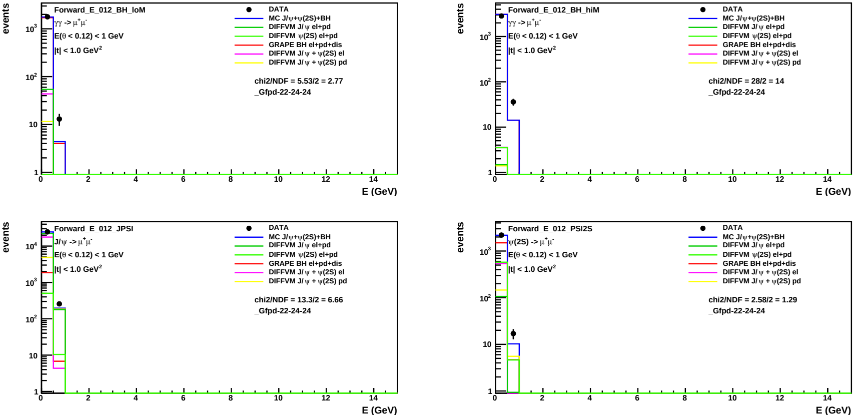
- **spectra like this are** used to evaluate the p.diss fractions (use longer "lever arm" then integrate it up to $|t| = 1.0$ GeV^2)
- using root package `TFractionalFitter`
- fitted $f_{p.diss} = 0.22$ and $= 0.24$ (JPSI and PSI2S, BH subtracted)
- **p.diss take over elastic around $\sim$ 1 GeV^2**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

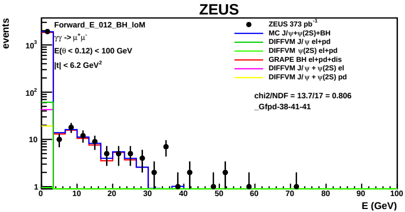
- **Forward Energy Flow:** $E(\theta < 0.12\,rad)$

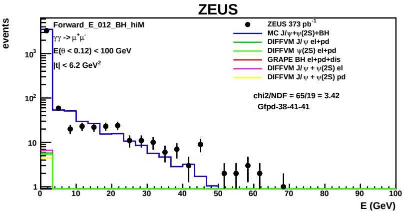
Forward energy flow in di-muon Mass bins

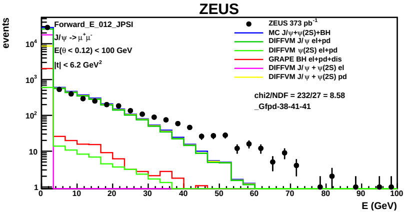


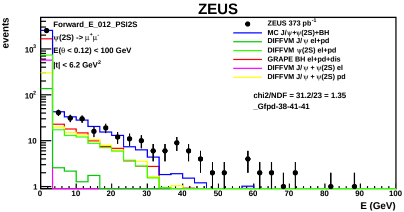
- 4 plots: BH-loMass: $M(\mu^+\mu^-) < 2.8$, BH-hiMass: $M(\mu^+\mu^-) > 4.0$, JPSI: $M(\mu^+\mu^-) \in (2.8 - 3.4)$, PSI2S: $M(\mu^+\mu^-) \in (3.4 - 4.0)$,
- using “standard” ZEUS/HERA-II anti-p.diss cuts
- $E(\theta < 0.12\,rad) < 1$ GeV, $|t| < 1$ GeV^2
- $f^{JPSI}_{p.diss} = 22\%$, $f^{PSI2S}_{p.diss} = 24\%$ (p.diss fractions from t-spectra templates fits)

Forward energy flow in di-muon Mass bins

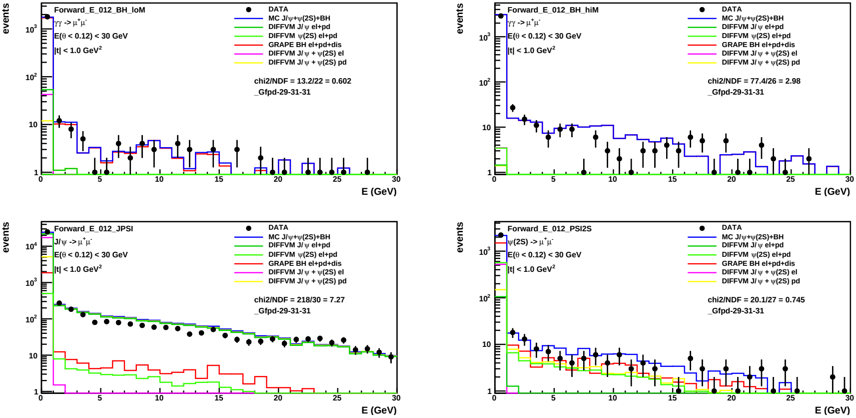






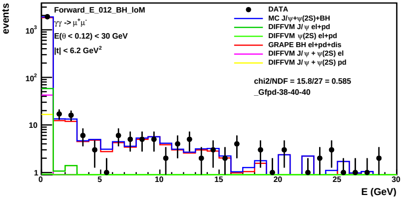


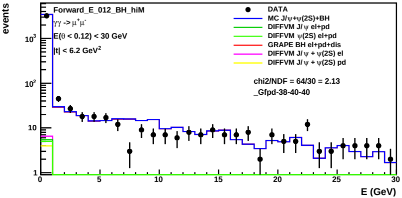
- 4 plots: BH-loMass: $M(\mu^+\mu^-) < 2.8$, BH-hiMass: $M(\mu^+\mu^-) > 4.0$, JPSI: $M(\mu^+\mu^-) \in (2.8 - 3.4)$, PSI2S: $M(\mu^+\mu^-) \in (3.4 - 4.0)$,
- relaxing anti-p.diss cuts
- $E(\theta < 0.12\,rad) < 100$ GeV, $|t| < 6.2$ GeV^2
- **inelastic J/ψ production not included in DIFFVM MC !**

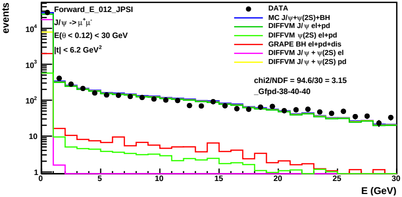


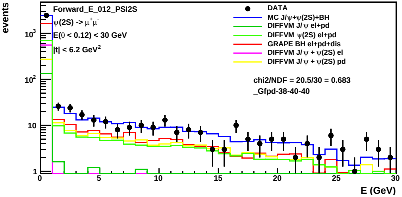
- relaxing anti-p.diss cuts, zoom into p.diss region
- $E(\theta < 0.12\,rad) < 30$ GeV, $|t| < 1$ GeV^2
- $f^{JPSI}_{p.diss} = 29\%$, $f^{PSI2S}_{p.diss} = 31\%$ (p.diss fractions from t-spectra templates fits)
- limited statistic outside J/ψ peak

Forward energy flow in di-muon Mass bins









- further relaxing anti-p.diss cuts
- $E(\theta < 0.12\, rad) < 30$ GeV, $|t| < 6.2$ GeV^2
- $f^{JPSI}_{p.diss} = 38\%$, $f^{PSI2S}_{p.diss} = 40\%$ (p.diss fractions from t-spectra templates fits)
- **independent cross-check of the estimation of p.diss fractions !**

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

Modeling of nucleon resonance state: DIFFVM

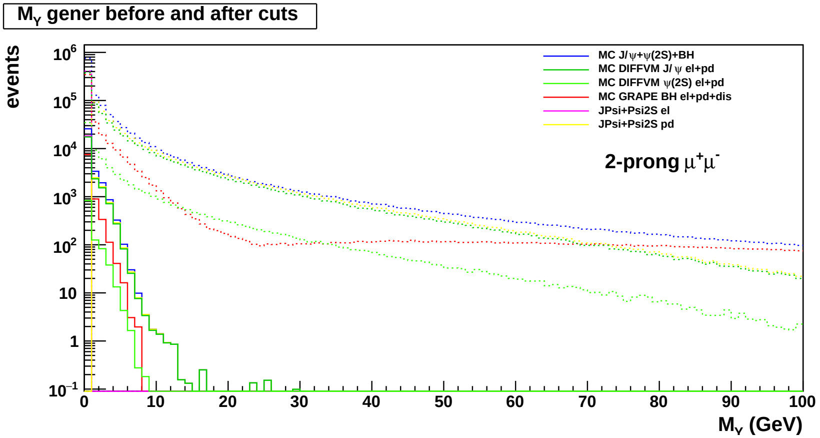
- $\frac{d\sigma}{dM_Y^2} \sim \frac{1}{M_Y^{2(1+\epsilon)}}$ for $M_Y^2 \geq 3.6$ GeV^2 (continuum region)
- $\frac{d\sigma}{dM_Y^2} \sim \frac{f(M_Y^2)}{M_Y^{2(1+\epsilon)}}$ for $M_Y^2 < 3.6$ GeV^2 (p resonance region)
- $f(M_Y^2)$ from the **fit the the p.diss cross section on deuterium**:
  $pD \rightarrow YD$ (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:

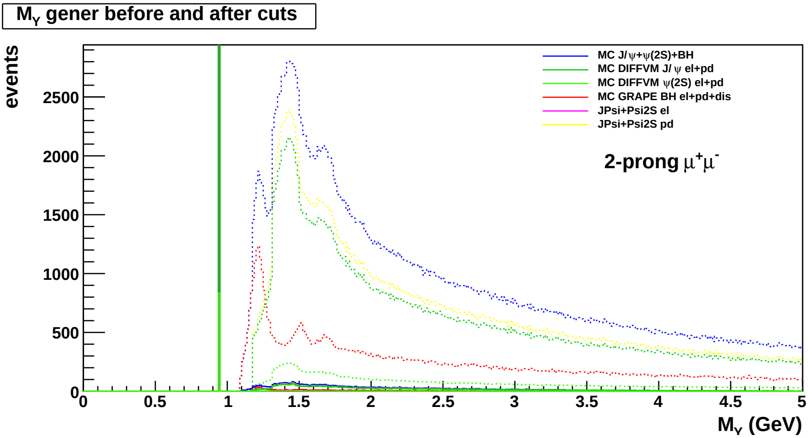
$$W^{\mu\nu} = W_1 \left(-g^{\mu\nu} + \frac{q^\mu q^\nu}{q^2} \right) + W_2 \frac{1}{M_P^2} \left(p_P^\mu - \frac{p_P \cdot q}{q^2} q^\mu \right) \left(p_P^\nu - \frac{p_P \cdot q}{q^2} q^\nu \right)$$

- $W_{1,2}(Q_P^2, M_{had})$ 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)



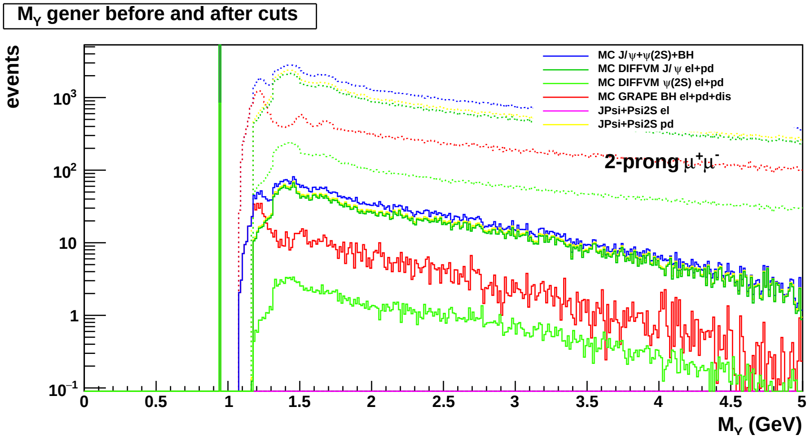
- M_Y at generator level (not measured quantity ! $\rightarrow$ lost in beam-pipe)
- before and after selection cuts
- GRAPE (BH) does include DIS scattering $\rightarrow$ rise of xsec. for large M_Y
- DIFFVM in DIS mode generates only **electroproduction** (with proton dissociation, “rapidity gap events”)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

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



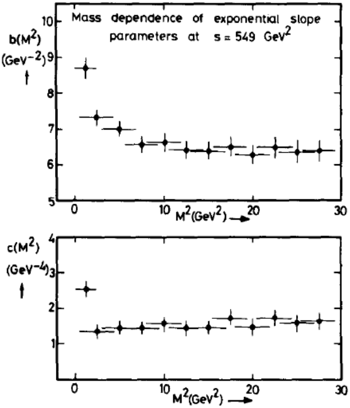
- different structure of nucleon resonances between GRAPE and DIFFVM (!?)
- which is right ?
- **how much it is important for p.diss BG subtraction ?**

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



- different structure of nucleon resonances between GRAPE and DIFFVM (!?)
- about $\sim$ 50% of p.diss events after anti-p.diss cuts come from nucleon resonances...
- **how much it is important for p.diss BG subtraction ?**

dependence of p.diss t-slopes on M_Y



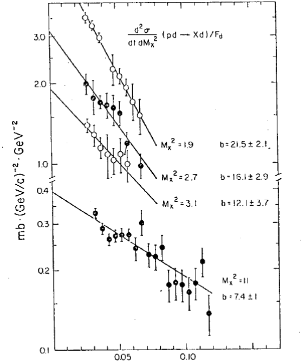
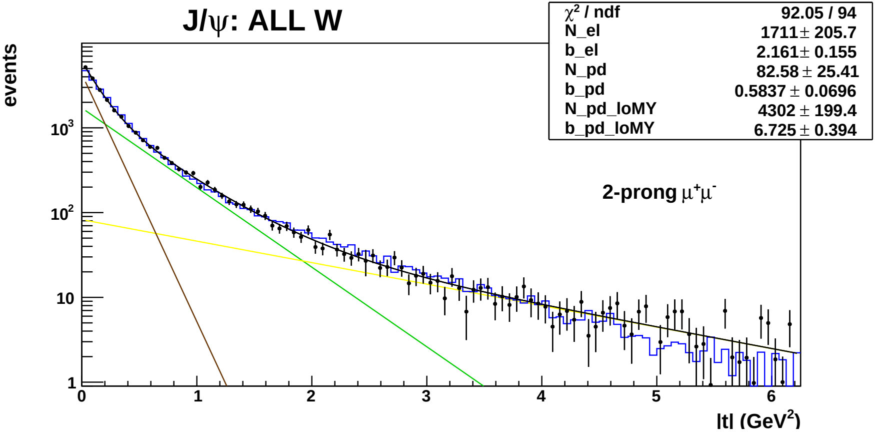


Figure 2 - Differential cross-sections vs. t for pp → Xp, extracted from pd → Xd, at p_{lab} = 275 GeV/c, for M_x^2 = 1.9, 2.7, 3.1, and 11 GeV².

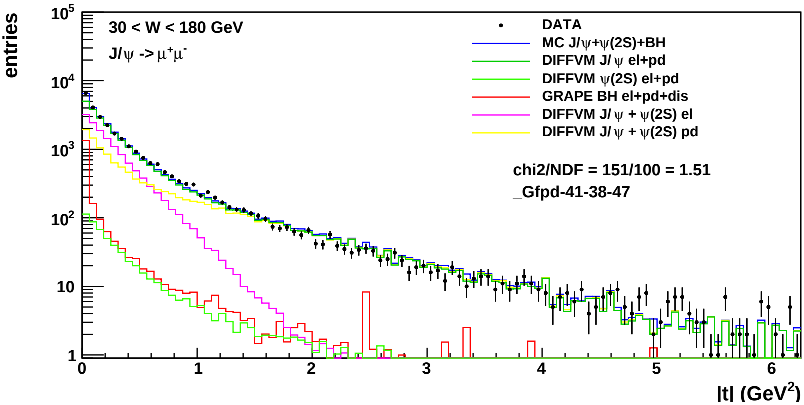
$$\frac{d^2\sigma}{dtdM_X^2}(pd \to Xd)$$

- 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 γp p-dissociative interactions ?
- if yes, it has big impact on the estimation of p.diss fraction (extrapolated from model dependent MC)

triple exp() fit to γp data

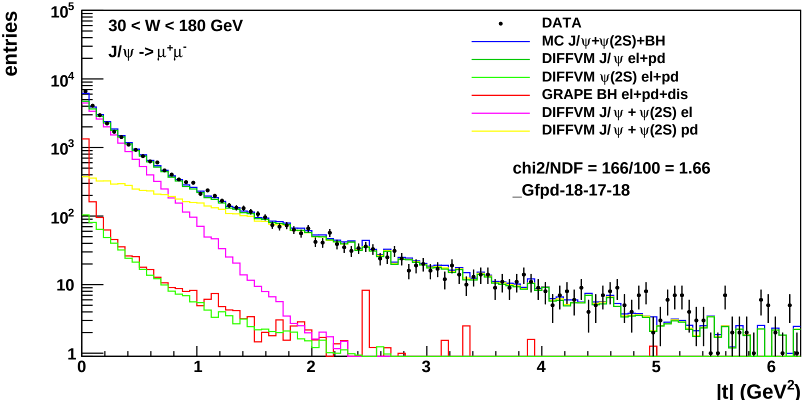


- J/ψ mass window, BH background subtracted
- **unconstrained triple** exp() **fit**, all $M_Y <\sim 6$ GeV (elastic selection)
- there is some room for third, steeper component $b_{pd-loMY} \approx 6.5$ GeV^{-2}
- but the elastic b_{el} slope becomes very unrealistic: $b_{el} \approx 2$ GeV^{-2}



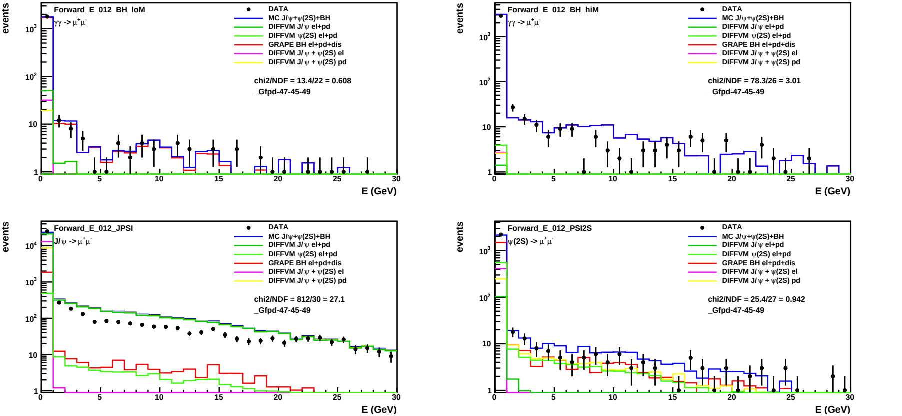
- **constraining the low M_Y component**
- reweighting the resonances $M_Y < 1.9$ GeV to $b_{pd-loMY} = 6.5$ GeV^{-2} (yellow histogram)
- DATA/MC agreement is as good as for two components (see next page)
- ... but the p.diss fraction increases from ~ 20 to $\sim 40\%$ (for $|t| < 1$ GeV^2)

Comparison with two exp() model



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

Forward Energy Flow with third exp() component



- reweighting the resonances $M_Y < 1.9$ GeV to $b_{pd-loMY} = 6.5$ GeV^{-2} (yellow histogram)
- third exp() scenario spoils the Forward Energy Flow...
- $f_{p.diss} = 41\%$ ($|t| < 1$ GeV^2)

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 $|t|$?)
- proton dissociation $\to$ **Forward Energy Flow** (cross check)

- 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...

2PR: 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 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 ($= 2p^{\mu}_{t,min}$)

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 2 pages

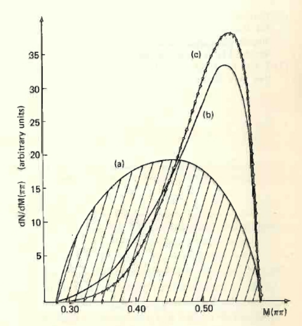
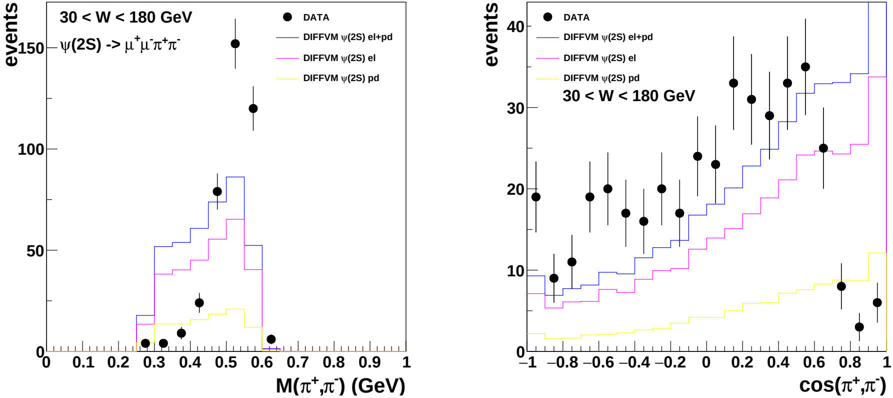
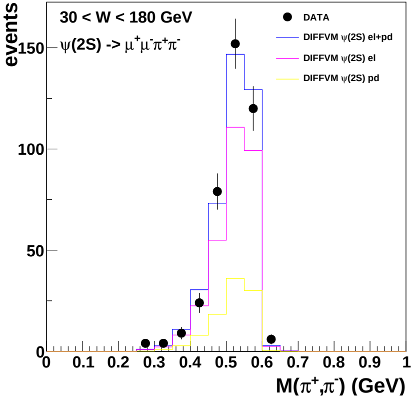


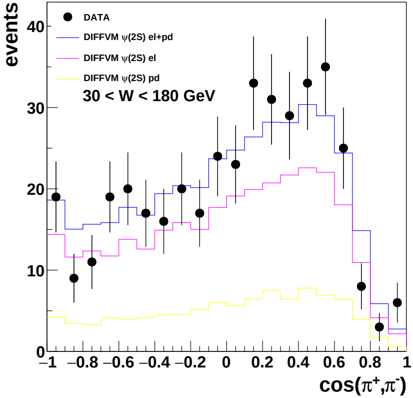
Fig. 4. Invariant mass distribution of two pions in S-state
Curve a $dN/dm_{\pi\pi} \propto$ phase space,
Curve b $dN/dm_{\pi\pi} \propto$ phase space $\times (s - 2\mu^2)^2$,
Curve c $dN/dm_{\pi\pi} \propto$ phase space $\times (s - 4\mu^2)^2$.



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

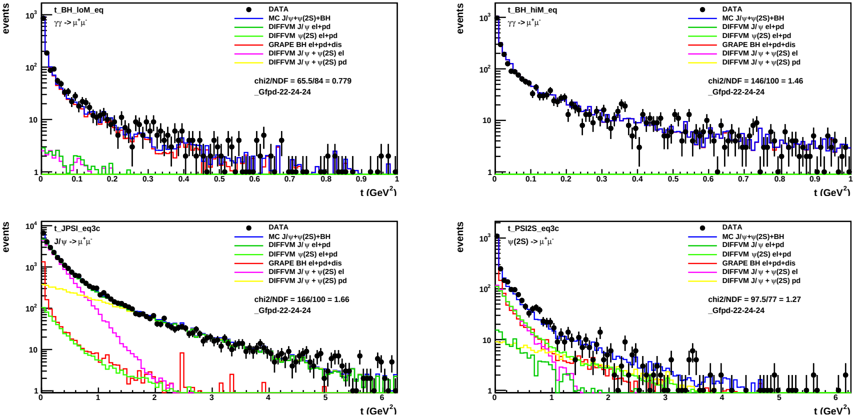
4-PRONGS: $M(\pi^-, \pi^+)$, $\cos(\pi^-, \pi^+)$





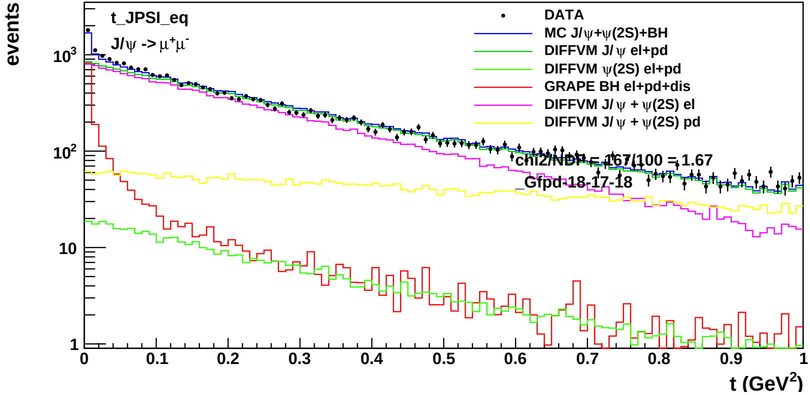
- $\psi' \rightarrow J/\psi + \pi^+\pi^-$
- $M(\pi^-, \pi^+)$, $\cos(\pi^-, \pi^+)$
- DIFFVM MC after pions phase space reweighting

2-prongs: $|t|$ distribution: 2-prong in mass bins



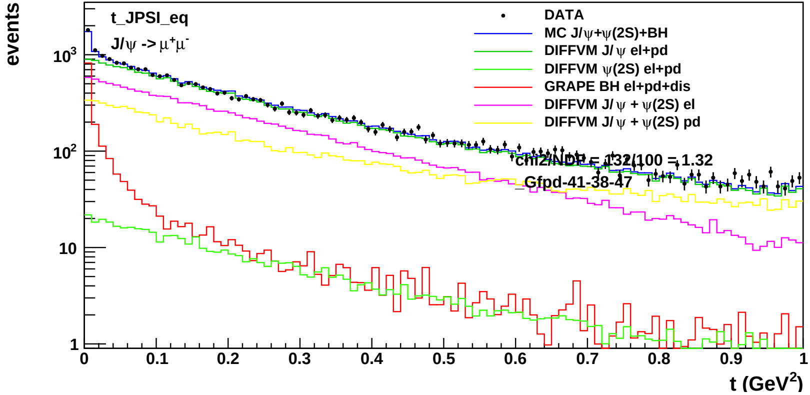
- BH-loMass, BH-hiMass, JPSI, PSI2S mass window
- non-exponential behavior for BH !
- $b_{el} = 4.6$ GeV^{-2}, $b_{pd} = 1.0$ GeV^{-2} (JPSI)
- $b_{el} = 4.3$ GeV^{-2}, $b_{pd} = 0.7$ GeV^{-2} (PSI2S)

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)

Introducing third exp() component on MC level (zoom for $|t| < 1.0\ \mathrm{GeV}^2$)

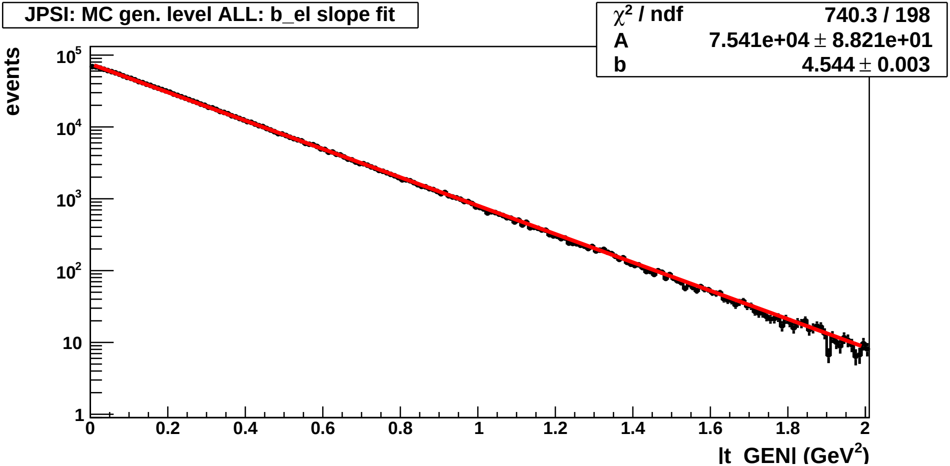


- reweighting the resonances $M_Y < 1.9$ GeV to $b_{pd-loMY} = 6.5\ \mathrm{GeV}^{-2}$ (yellow histogram)
- a bit better agreement in terms of χ^2 ...
- $f_{p.diss} = 41\%$ ($|t| < 1\ \mathrm{GeV}^2$) !?
- which scenario is realized by Nature ?
- $\rightarrow$ selection of clean p.diss, low M_Y events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

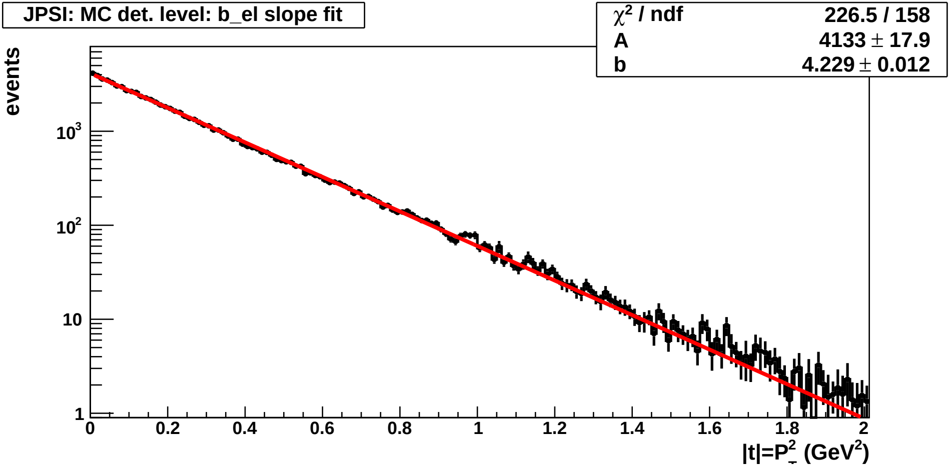
MC DIFFVM generator level

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

elastic JPSI: MC DIFFVM generator level

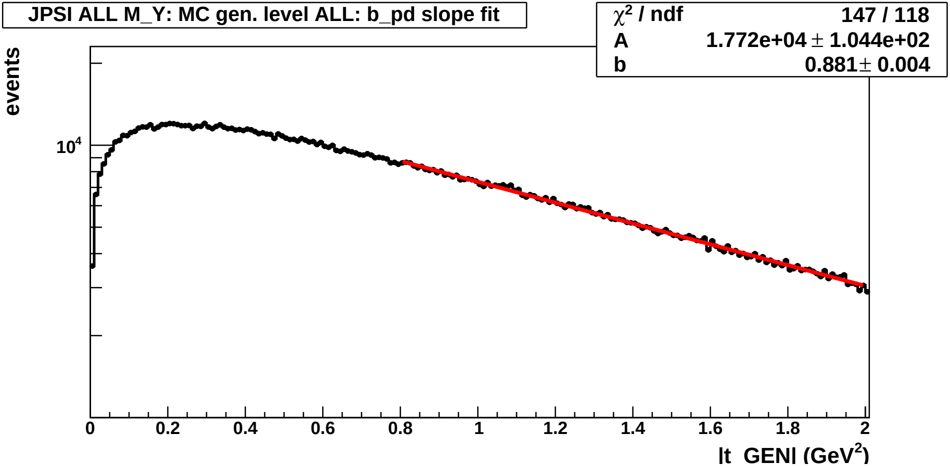


- elastic JPSI: generator level “true” $|t|$-distribution before cuts, (calculated using gen-level 4-vectors including scattered e')
- reweighted to: $b_{el} = 4.6$ GeV^{-2} (realistic example)



- 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 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)

p.diss JPSI: MC DIFFVM generator level

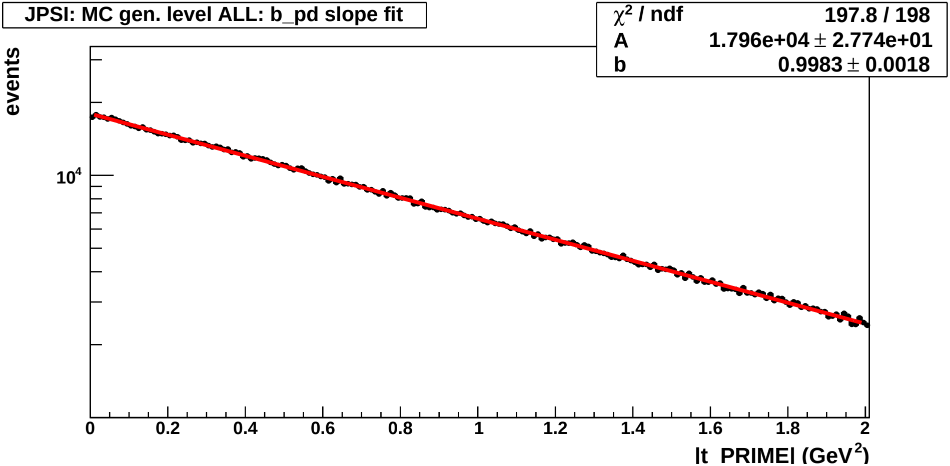
- t' variable corrected for threshold effect:

```
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);
```

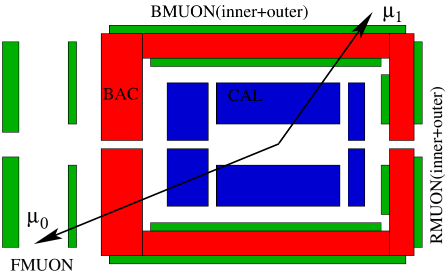
p.diss JPSI: MC DIFFVM generator level



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

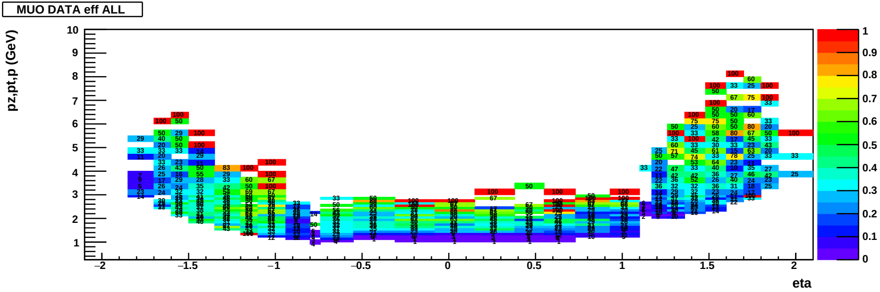
Muon effic. corrections: TAG and PROBE

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

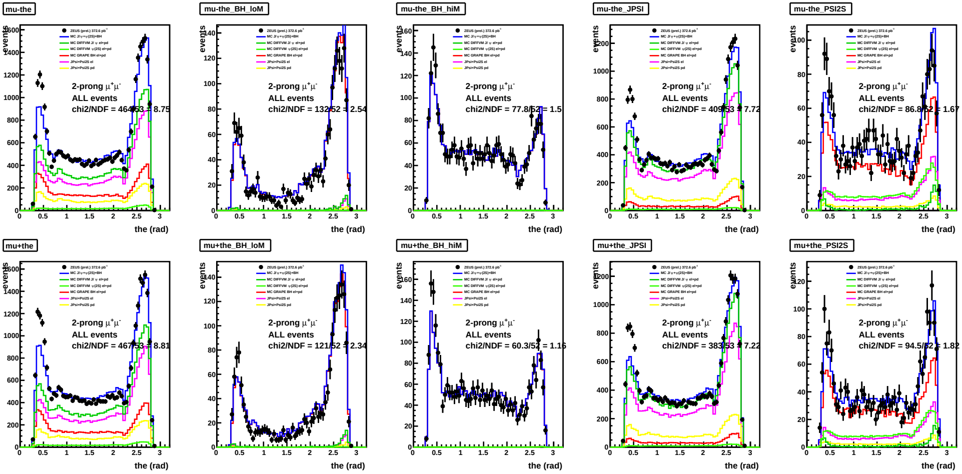


- one step correction for (FLT and SLT and TLT and off-line REC)
- separate maps for F/B/R/MUO, BAC and CAL (off-line only)
- evaluated for single muon in (pt_{eff},η) bins, where as pt_{eff} is used:
  (motivated by the CAL/BAC geometry and scaling of the muon path length)
  - p in Forecap
  - p_t in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

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

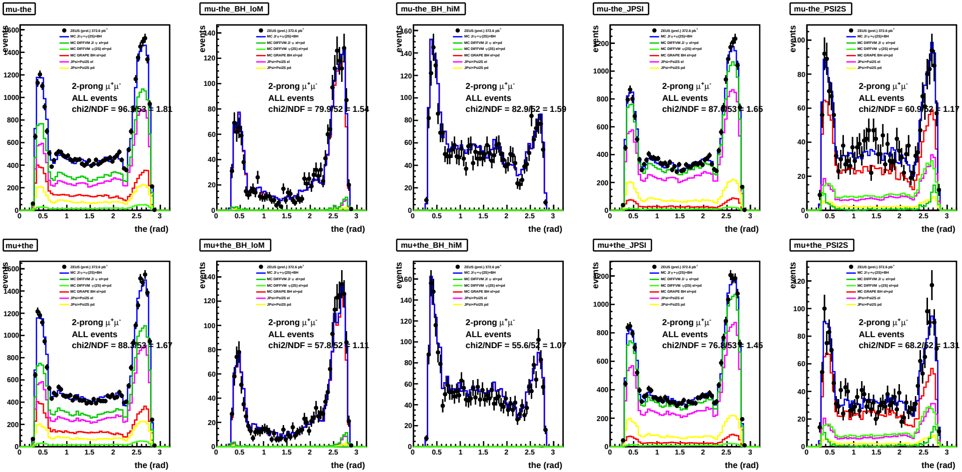


- **muon tomography**
- probability (%) to fire FLT-SLT-TLT-REC chain by single muon on ($p_z, p_t, p; \eta$) grid
- X-axis (along eta): Rear-MUO, Barrel-MUO, Forward-MUO detectors
- only events with $M(\mu^+, \mu^-) < 6$ GeV
  (ie. in the phase space range of di-muon mass fits)
- current choice for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



- top: $\theta_{\mu-}$, bottom: $\theta_{\mu+}$
- ALL events, BH-loM, BH-hiM, J/ψ peak, ψ' 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/ψ peak, ψ' peak
- good agreement in all mass windows (validation of muon corrections)
- (different processes, different $\mu^\pm$ angular/momentum distributions, different boost)