Nucleon structure in lepton-nucleon interactions photoproduction

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European Commission

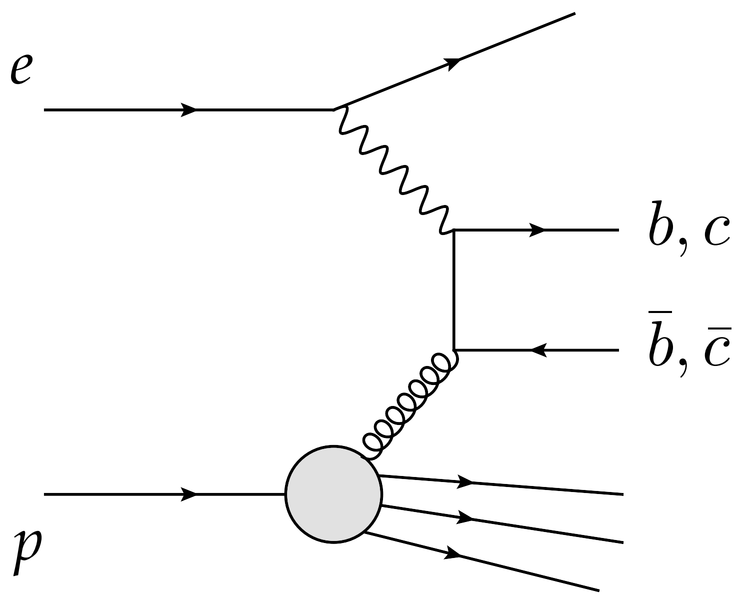
PHOTON 2019
Frascati, Italy
June 3-7, 2019

Outline

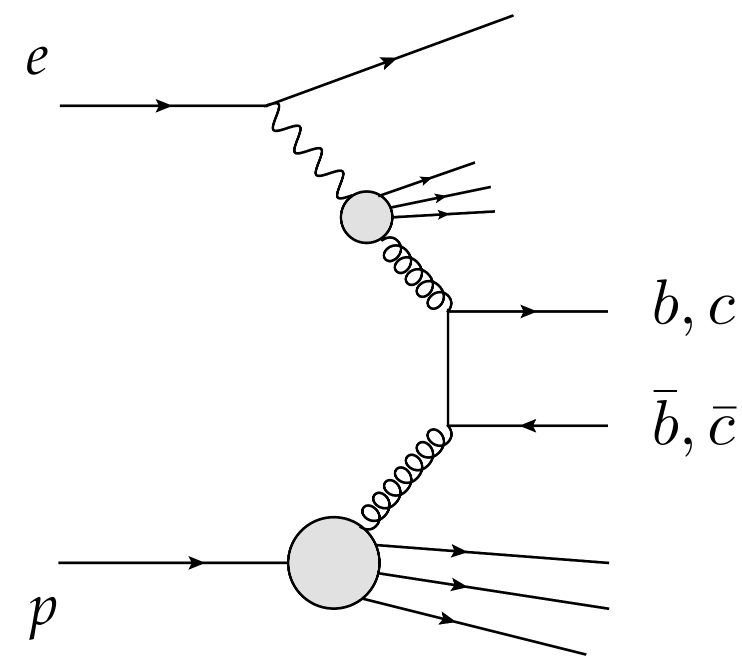
- Charm and beauty photoproduction
- Exclusive processes
- Search for new resonance states
- Longitudinal double-spin asymmetries

Charm and beauty photoproduction

boson-gluon fusion



direct photon process



resolved photon process

perturbative QCD, hard scales:

- large c, b mass
- large c, b p_T

c/b-tagging

- $c \to D,\ D^*$ + full reconstruction

- jets of b, c quarks via single lepton tags or displaced vertices:
  - long heavy-flavoured hadron lifetime: large impact parameter of decay (lepton) tracks wrt. primary vertex
  - large heavy-flavoured hadron mass: broad $P^{\mu}_{T,rel}$ wrt. jet direction or large invariant mass of secondary vertex

efficient at large b, c-quark transverse momentum p_T

- double tags
  - μ and D*
  - 2 leptons

access to lower b, c-quark transverse momentum p_T

pQCD calculations

@ NLO in α_S

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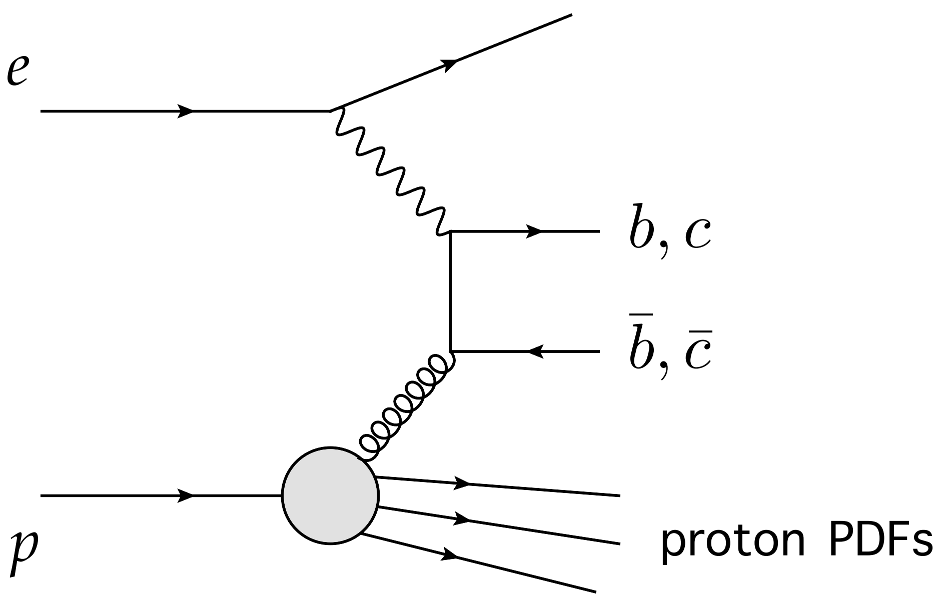

direct-photon process

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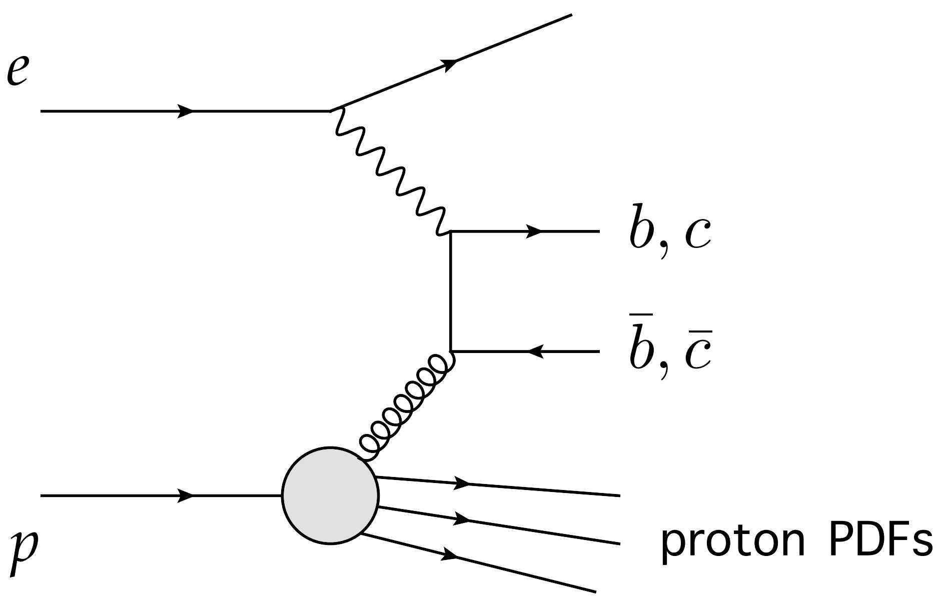

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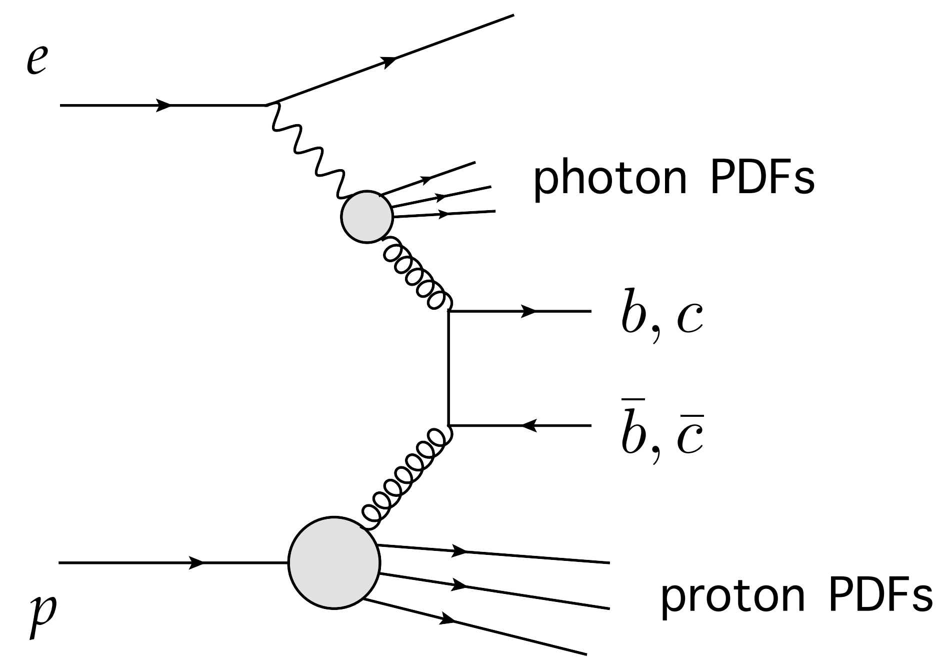

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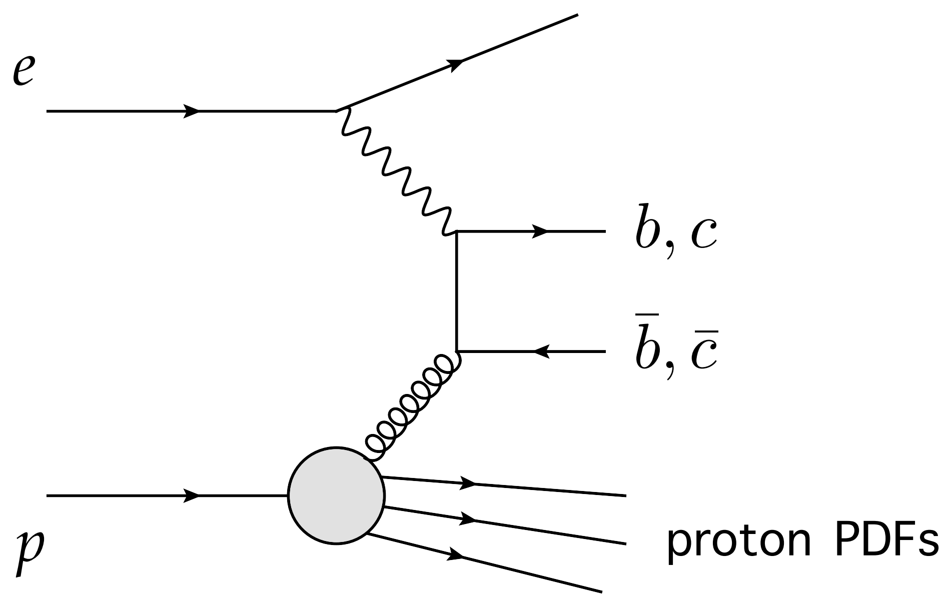

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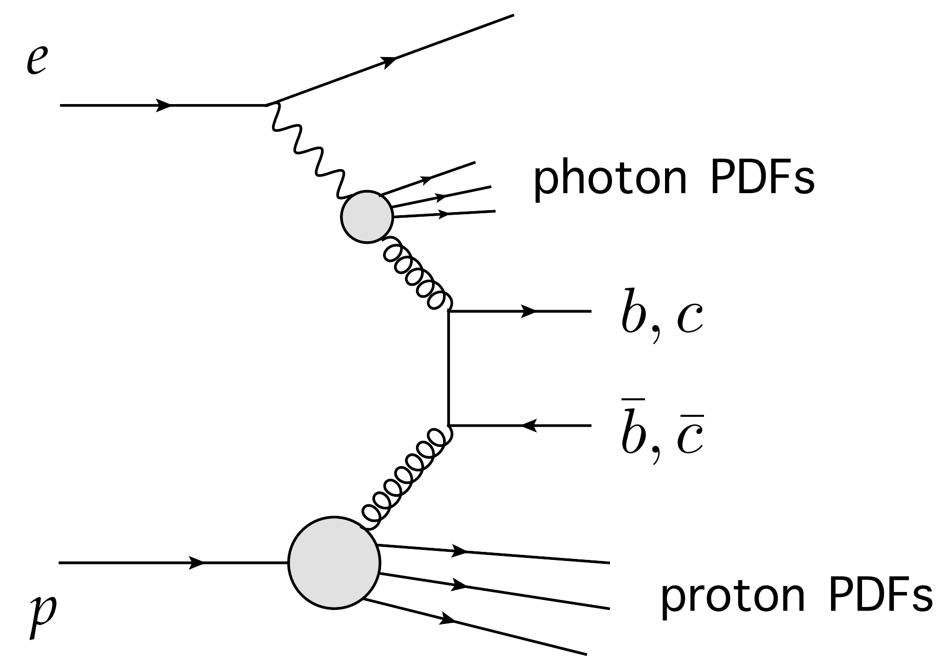

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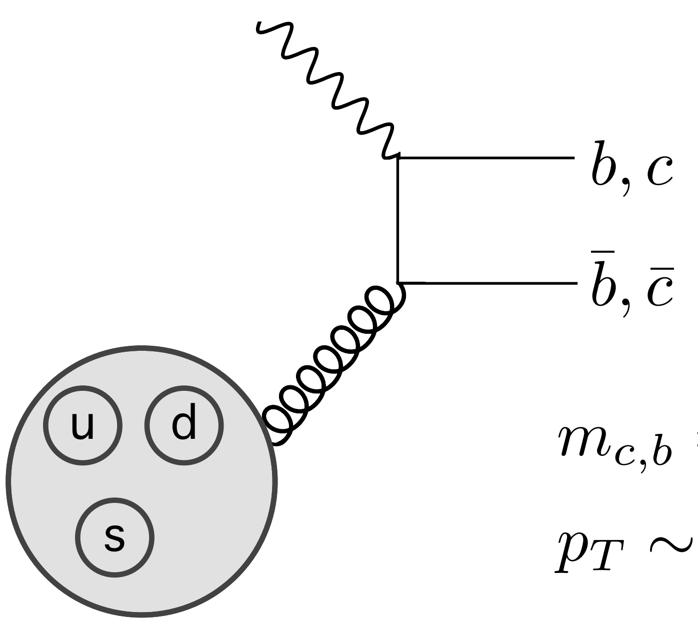

$m_{c,b} \neq 0$

$p_T \sim m_{c,b}$

massive scheme

pQCD calculations

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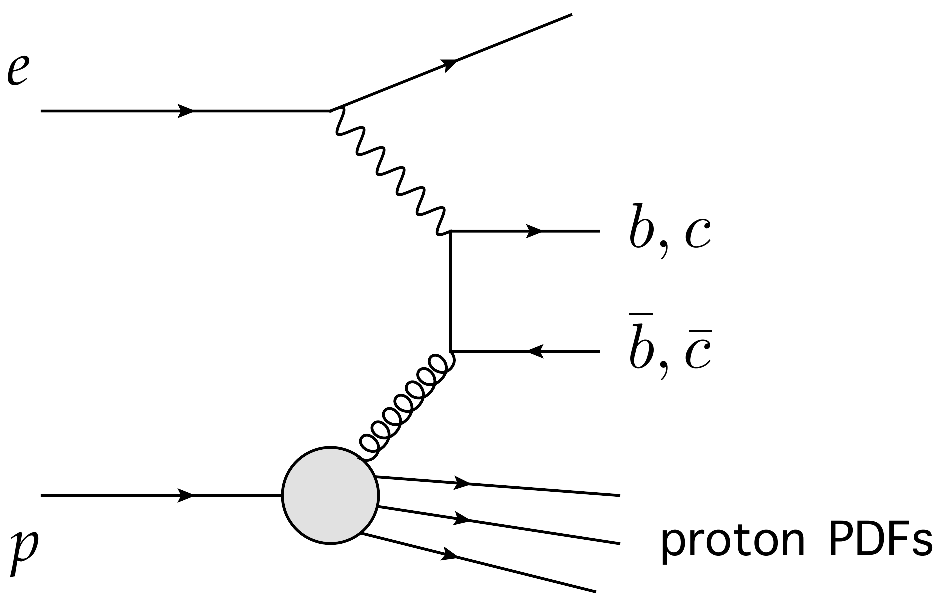

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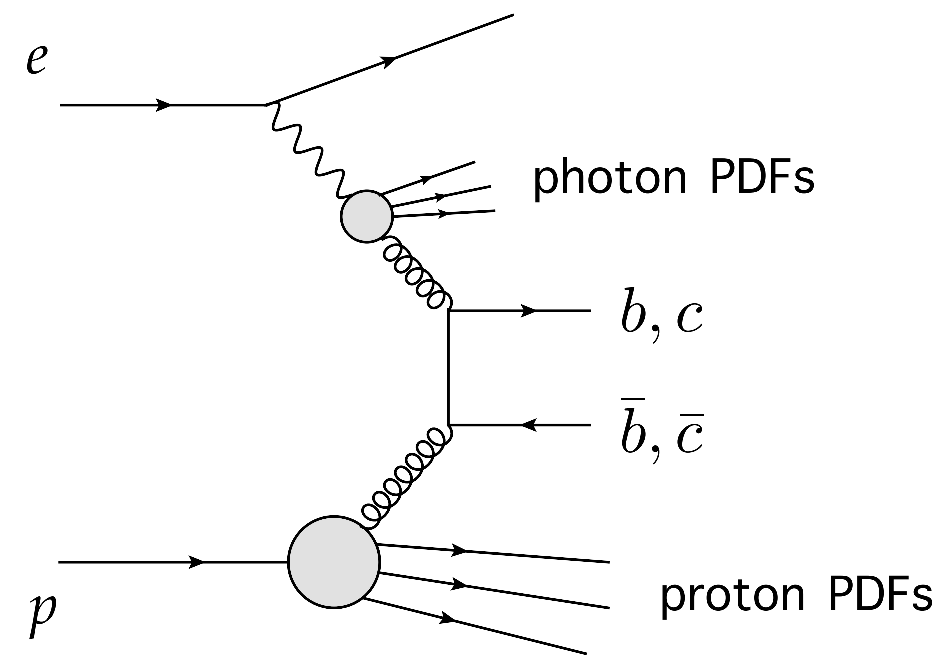

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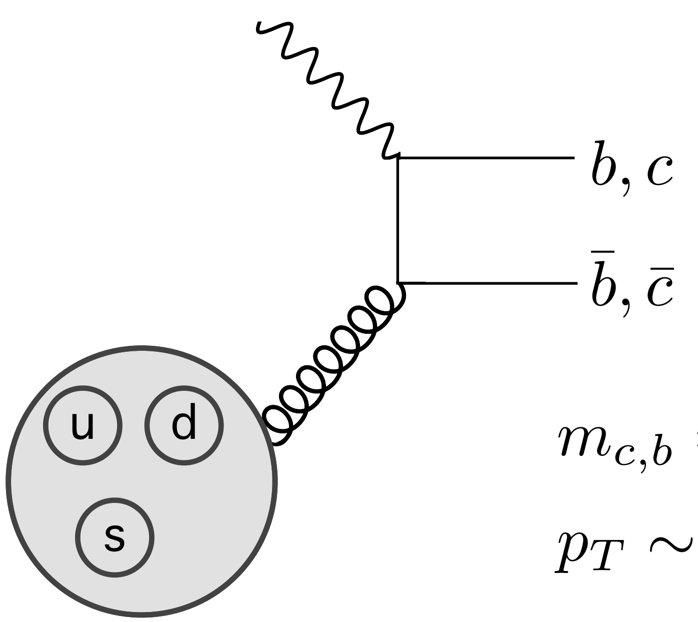

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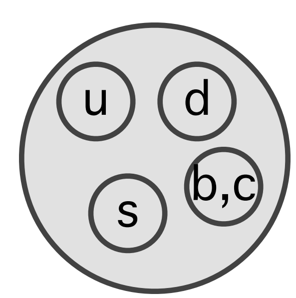

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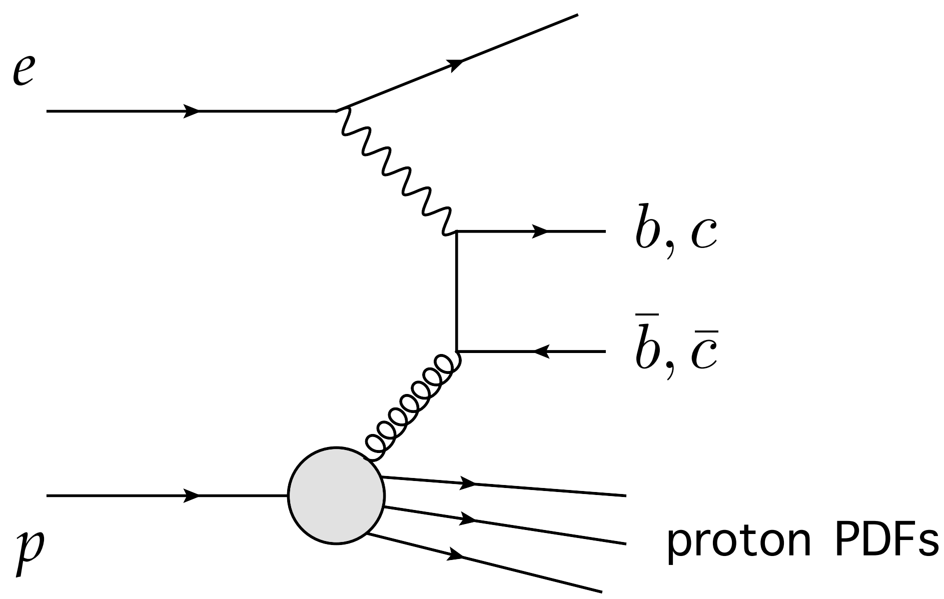

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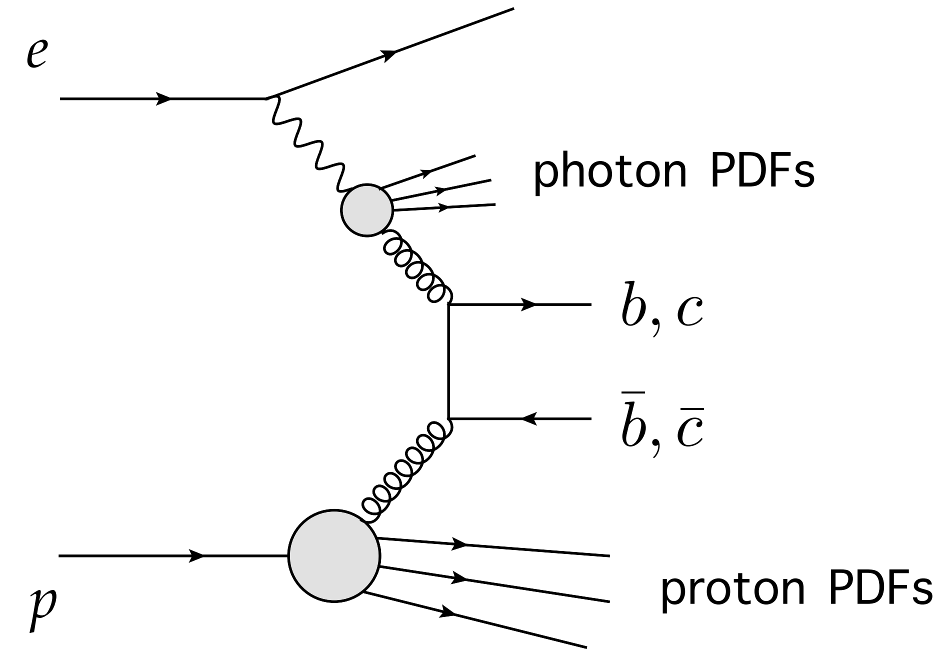

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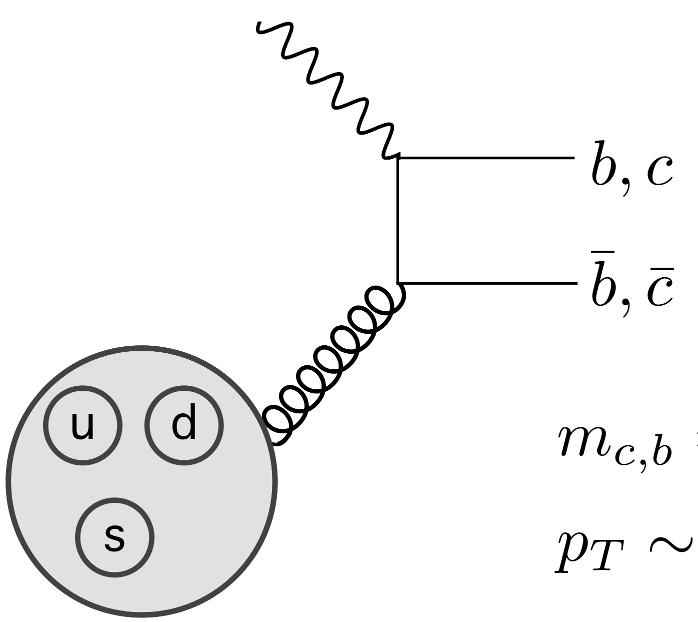

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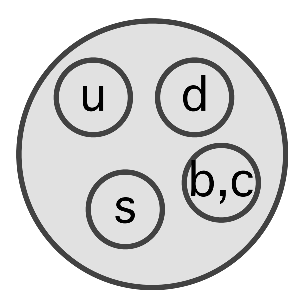

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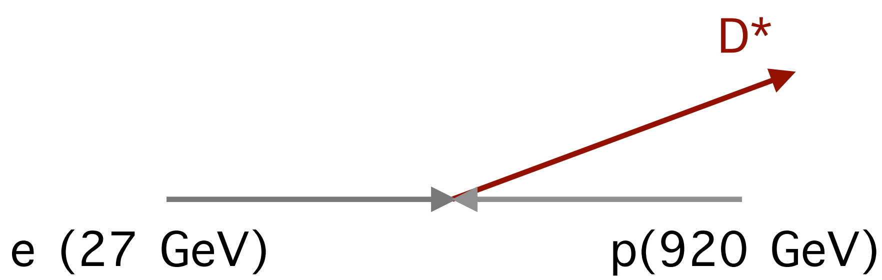
massless scheme

combination of both:
general-mass
variable flavour
number scheme
(GMVFNS)

Inclusive D* and dijet D*



$$P_T(D*) \gtrsim 2 \text{ GeV}$$

$$Q^2 < 2 \text{ GeV}^2 \qquad |\eta(D*)| < 1.5$$

$$100 \text{ GeV} < W_{\gamma p} < 285 \text{ GeV}$$

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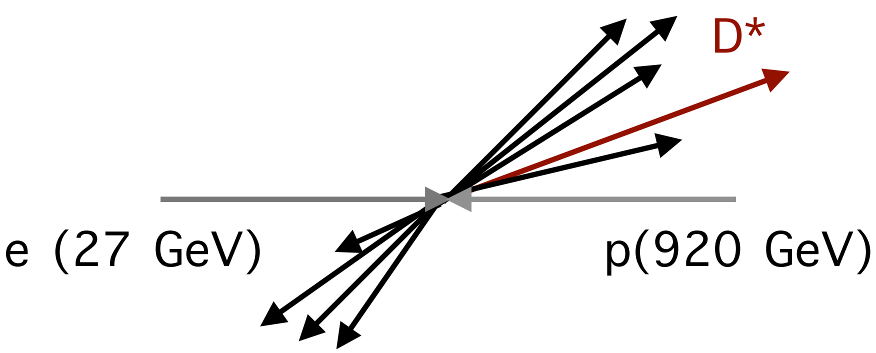

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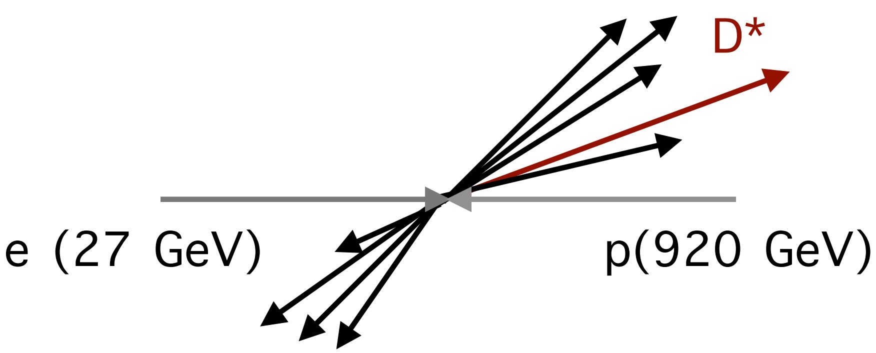

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- jets:
  - extra hard scale for pQCD
  - distinction direct (x_γ=1) and resolved (x_γ<1) process

$$x_\gamma = \frac{\sum_{\text{jets}}(E - p_z)}{\sum_{\text{HFS}}(E - p_z)}$$

(HFS= hadronic final-state particles)

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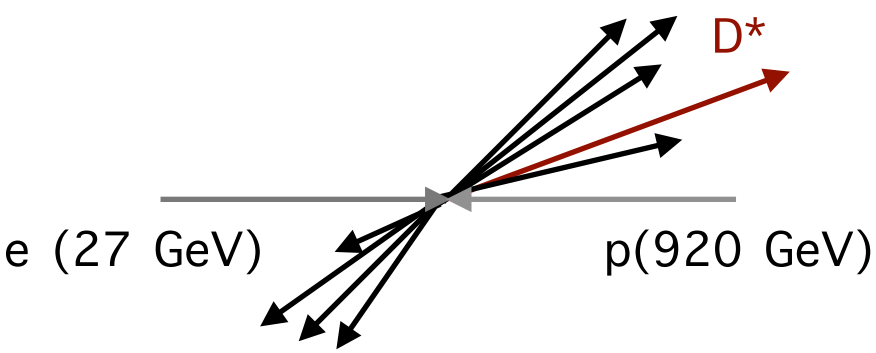

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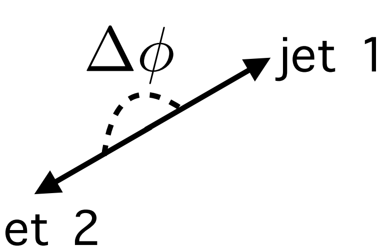
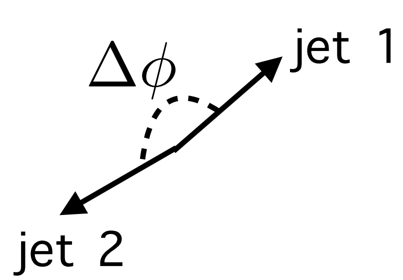
- $\Delta\phi = 180^\circ$ LO

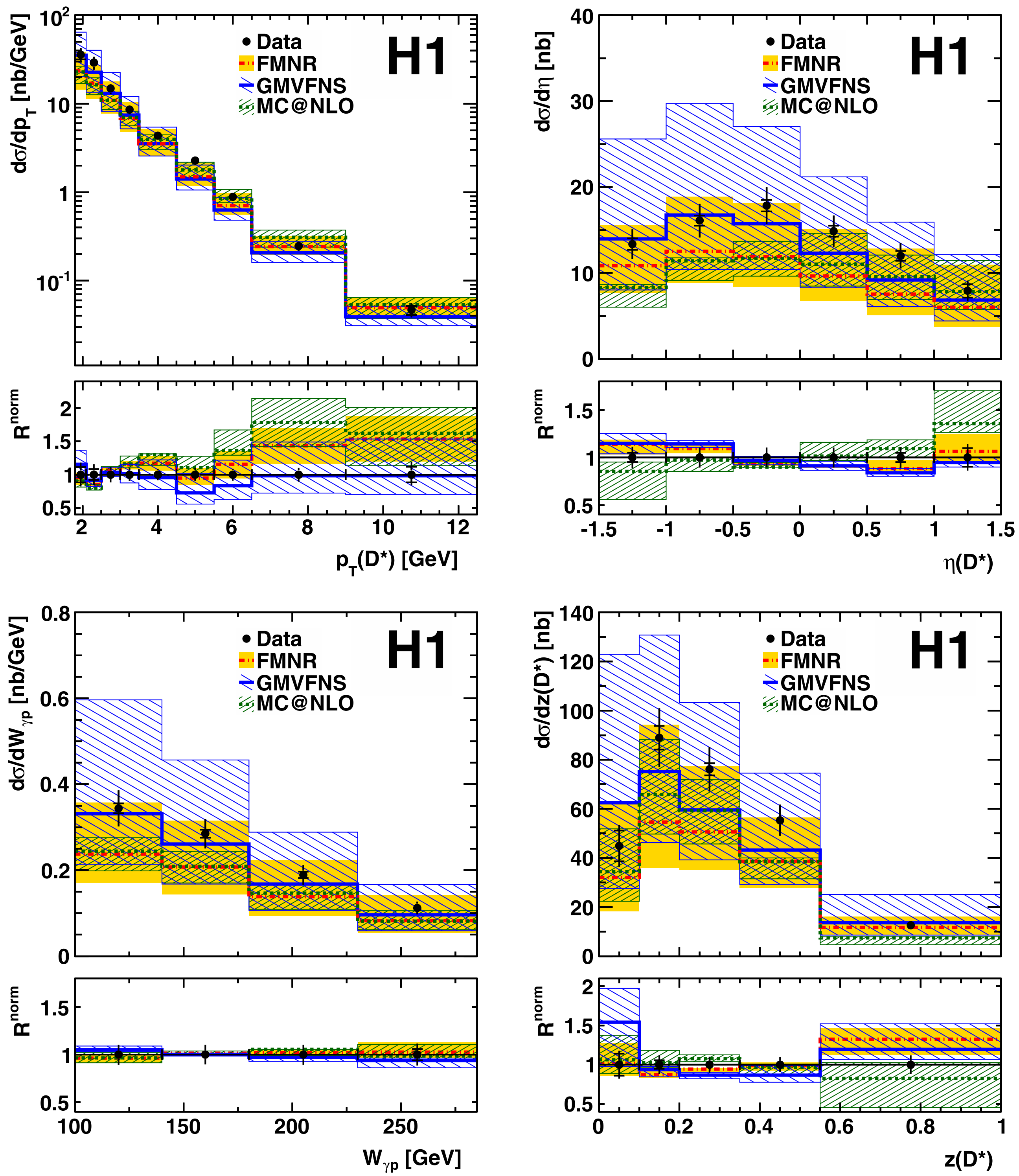


$\Delta\phi < 180^\circ$ NLO initial k_T



Inclusive D* results

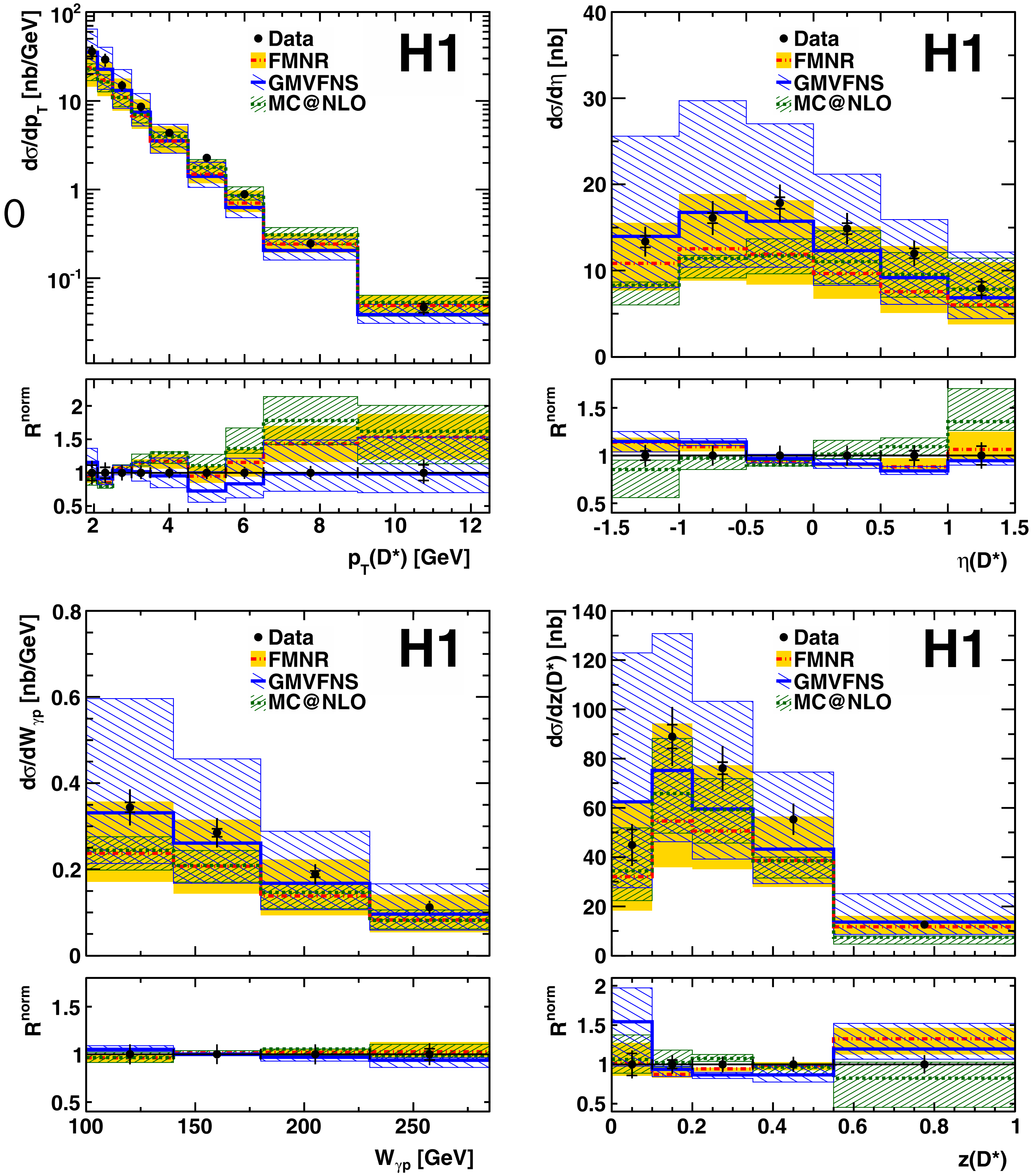
Eur. Phys. J. C 72 (2012) 1995



Inclusive D* results

Eur. Phys. J. C 72 (2012) 1995

- QCD calculations
  - NLO
  - collinear factorisation
  - direct+resolved photon
  - proton PDF: HERAPDF1.0



- FMNR
  - massive scheme
  - photon PDF: GRV-G HO
- MC@NLO
  - massive scheme
  - photon PDF: GRV-G HO
  - parton showering: HERWIG
- GMVFNS
  - photon PDF: AFG04

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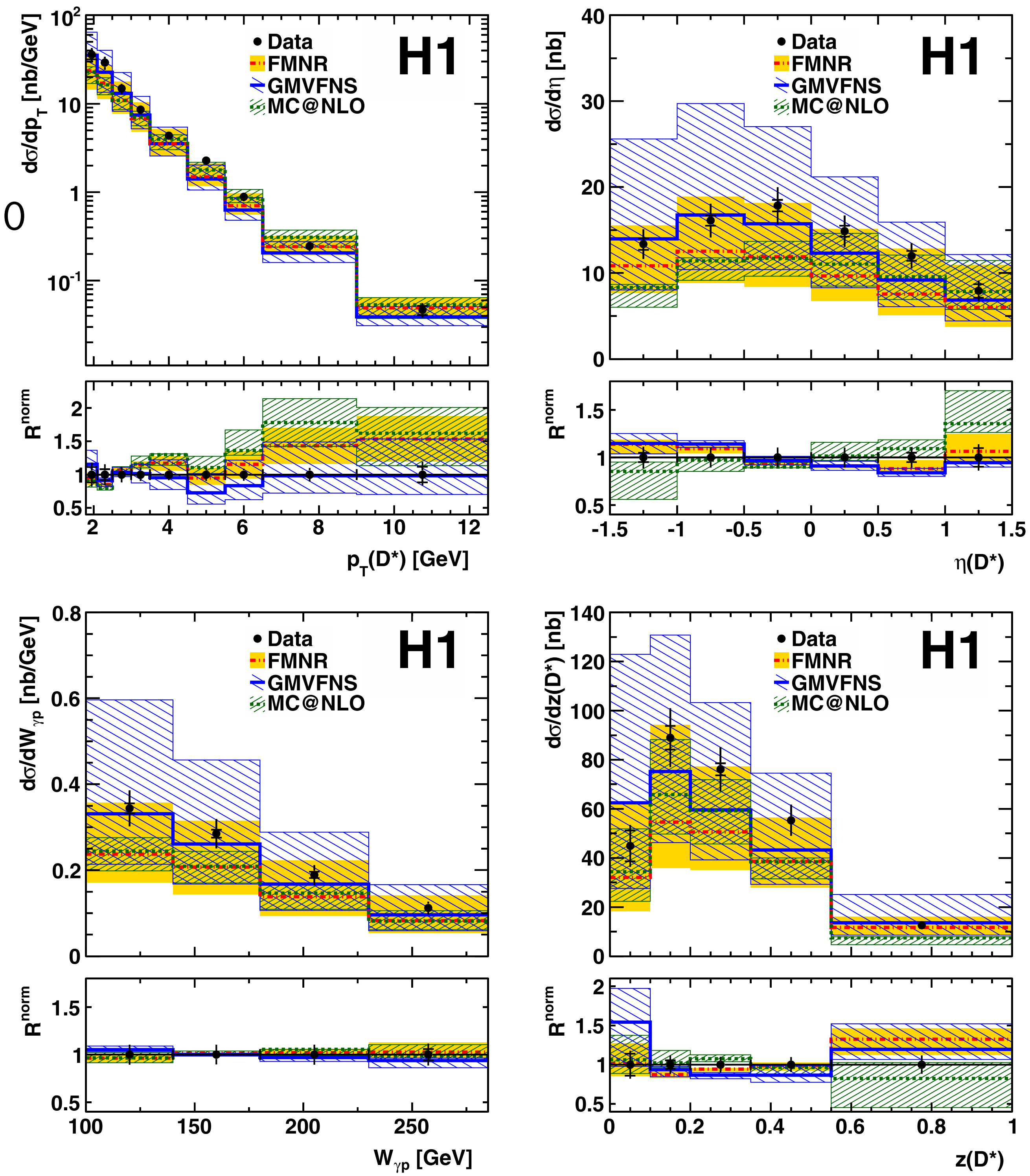
$$R^{\text{norm}} = \frac{\frac{1}{\sigma_{\text{vis}}^{\text{calc}}} \cdot \frac{d\sigma^{\text{calc}}}{dY}}{\frac{1}{\sigma_{\text{vis}}^{\text{data}}} \cdot \frac{d\sigma^{\text{data}}}{dY}}$$



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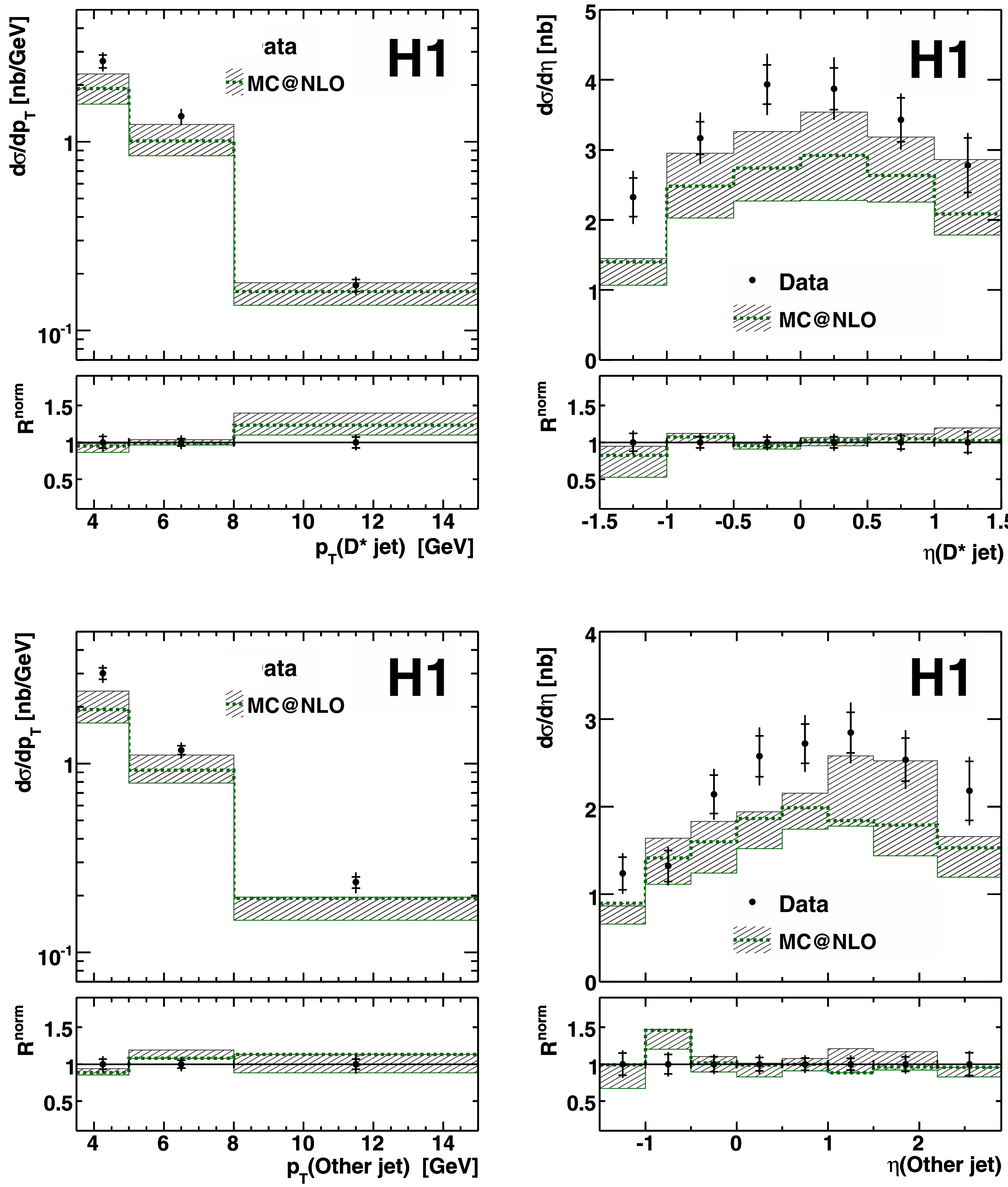

- other jet is more forward:
  - slightly different η cuts
  - origin: not always c quark

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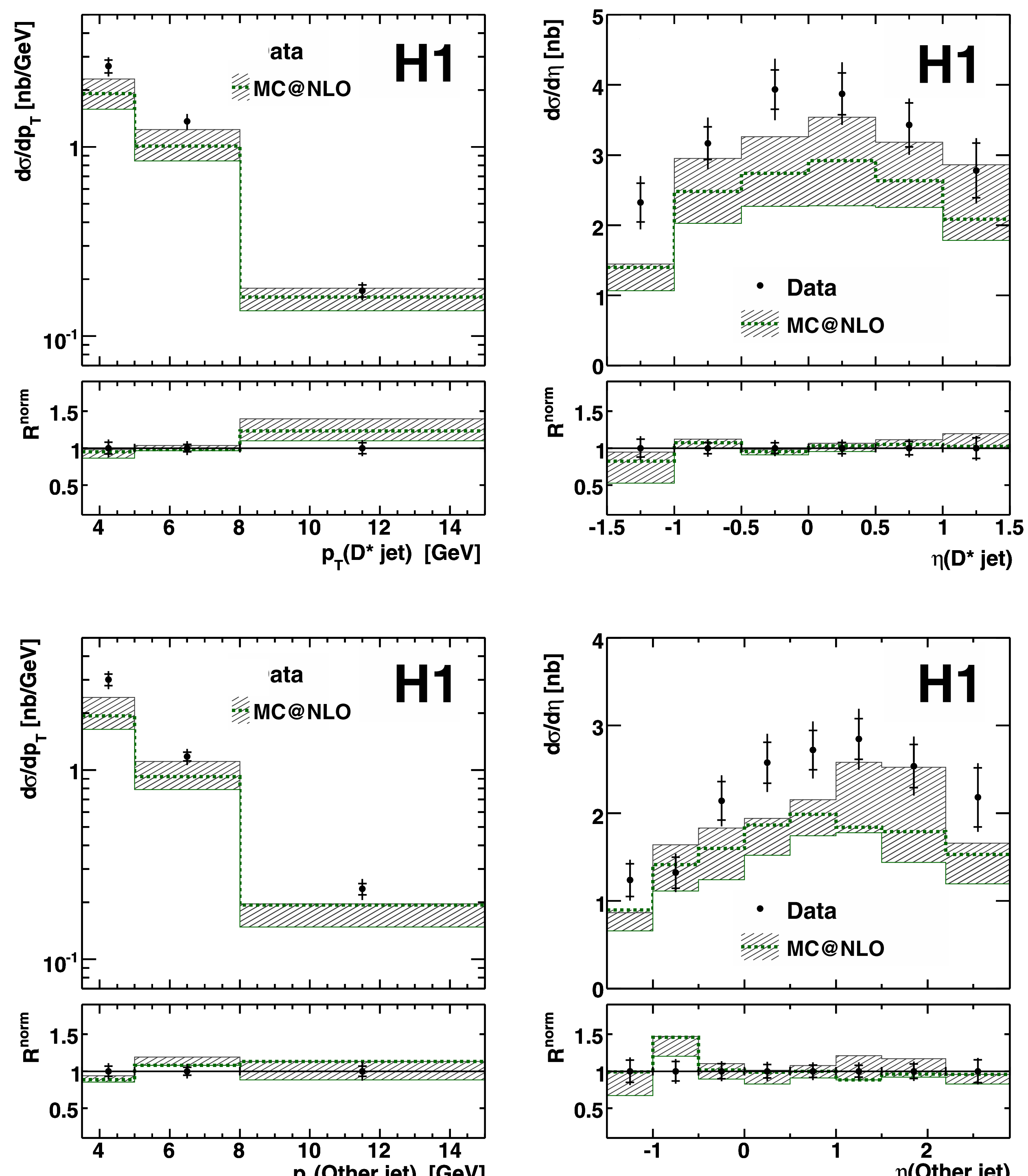

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D* tagged dijet correlations

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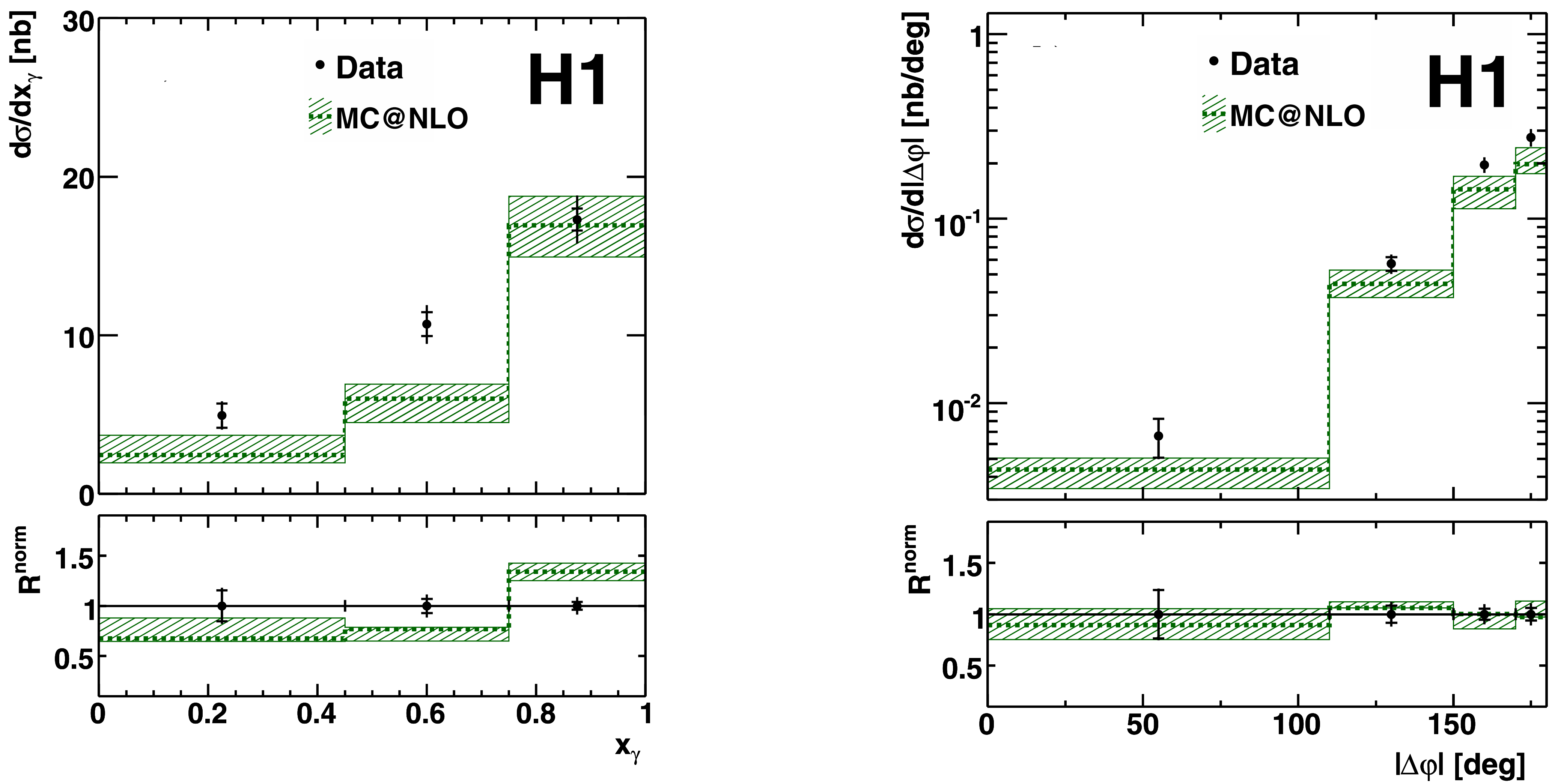

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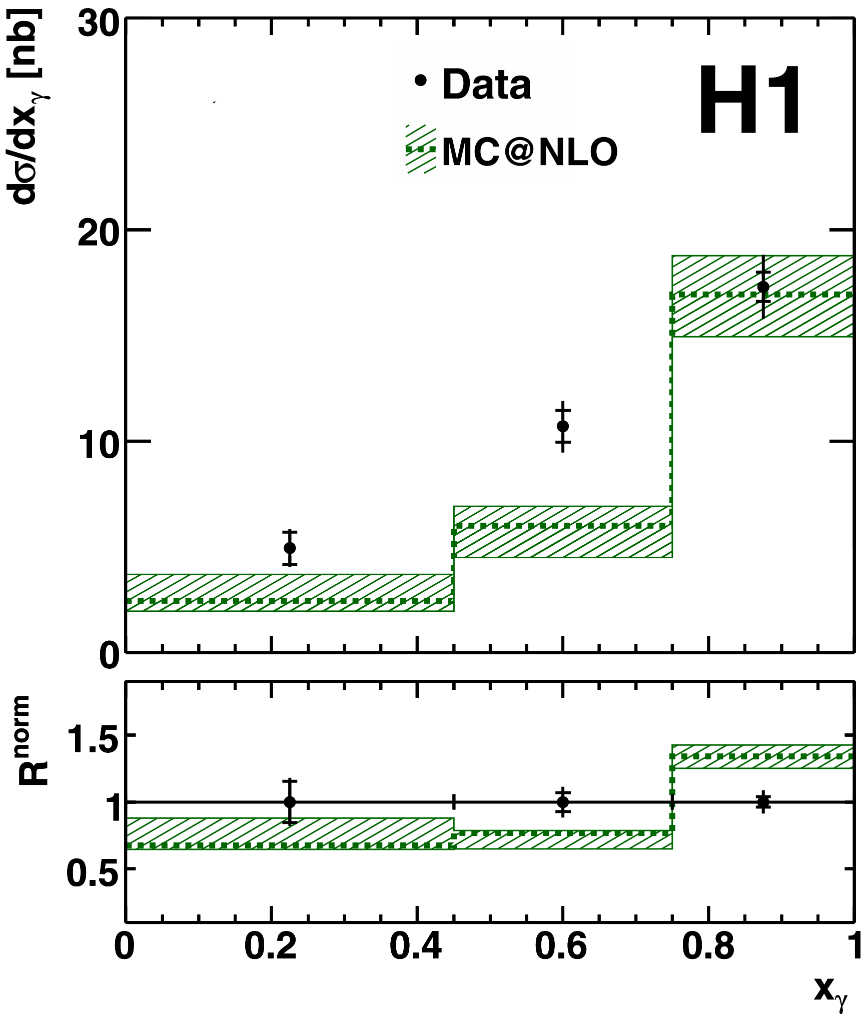

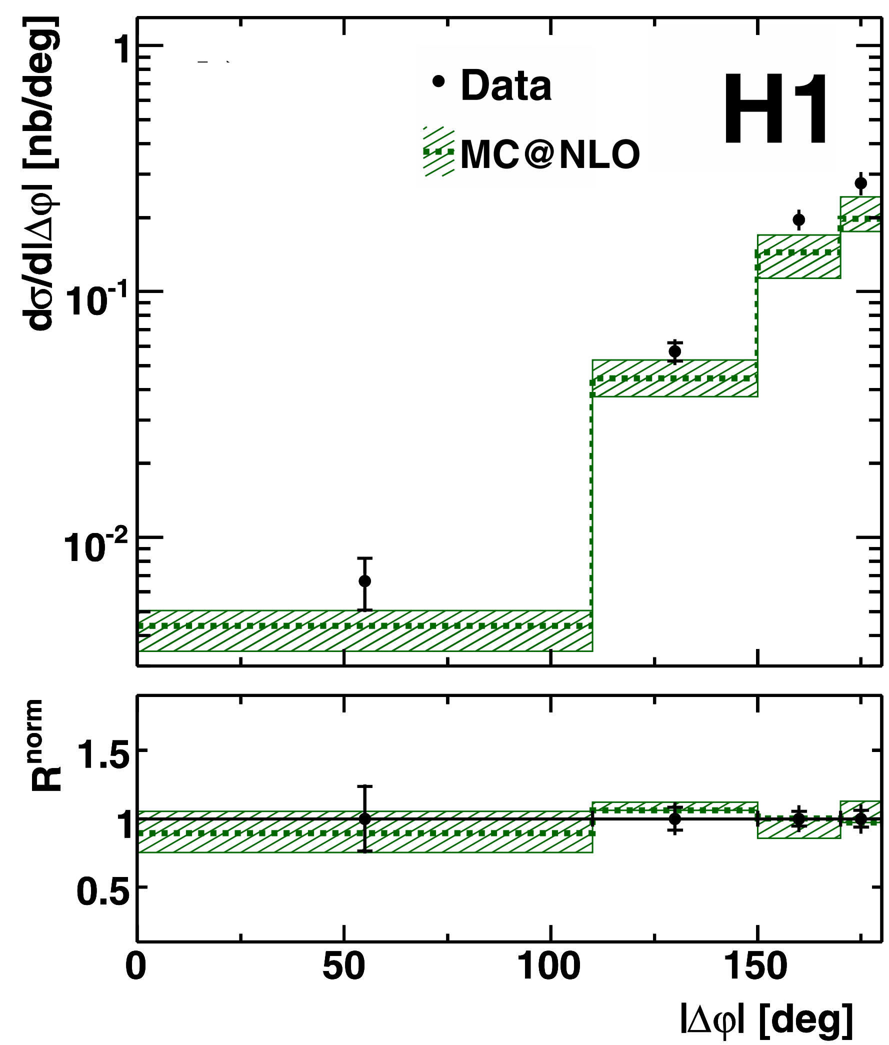

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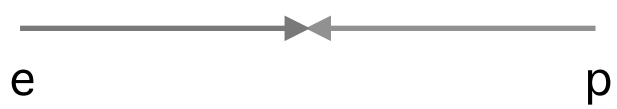
Heavy-quark jets



$Q^2 \leq 1 \text{ GeV}^2$

$\sqrt{s} = 320 \text{ GeV} \quad 0.2 < y < 0.8$

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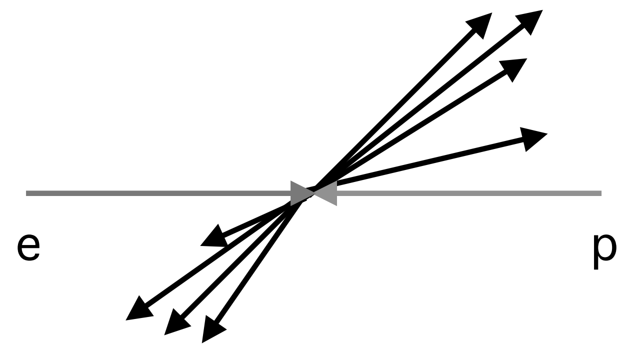

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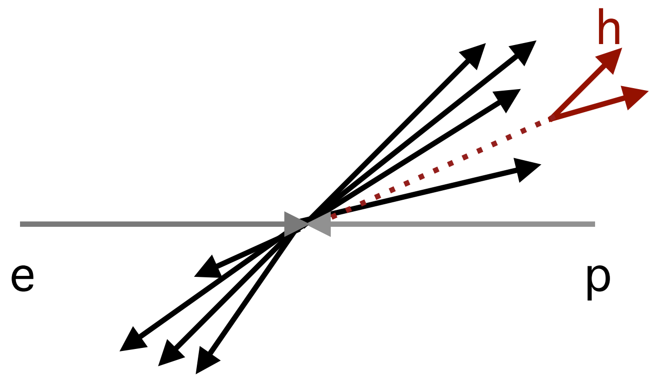

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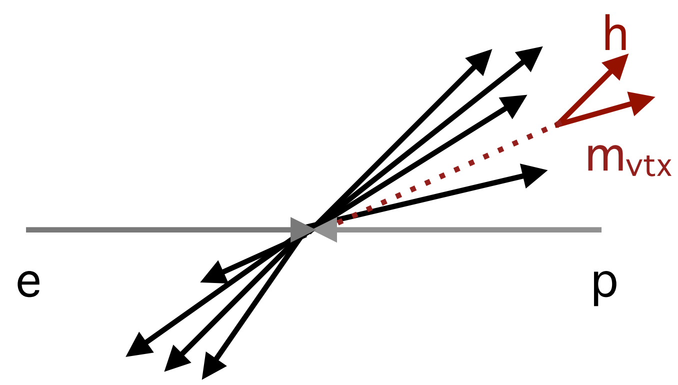

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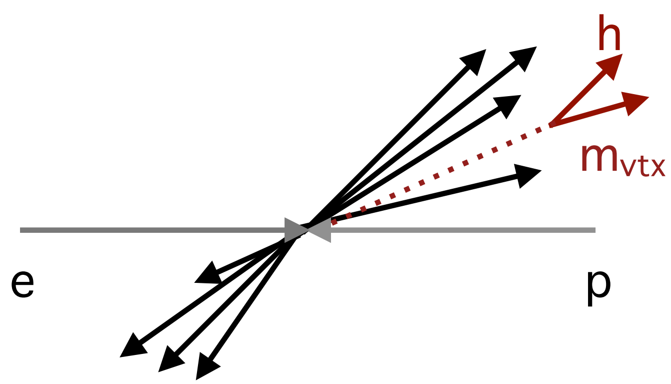

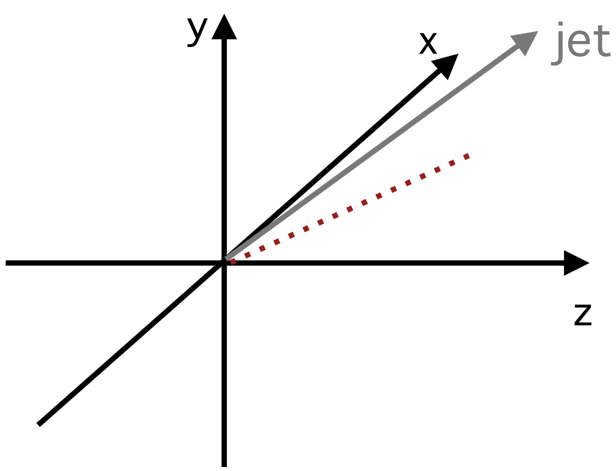

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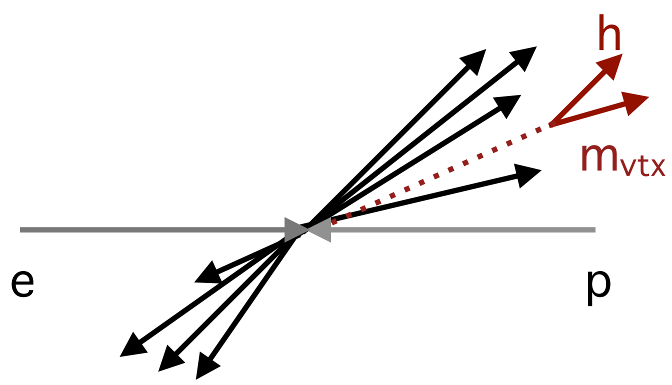

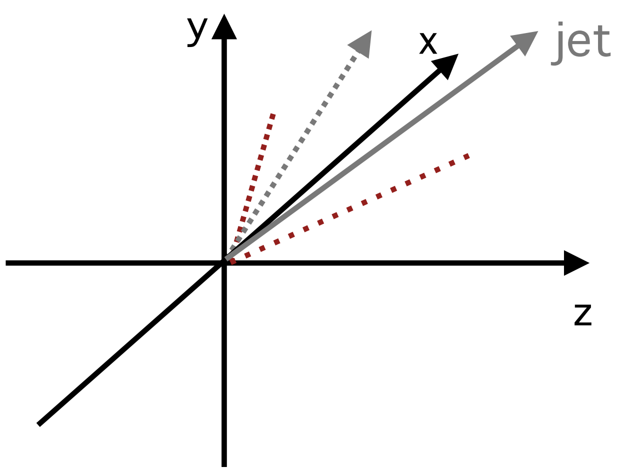

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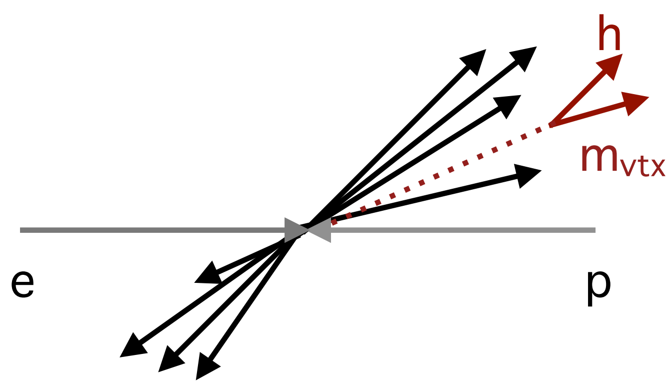

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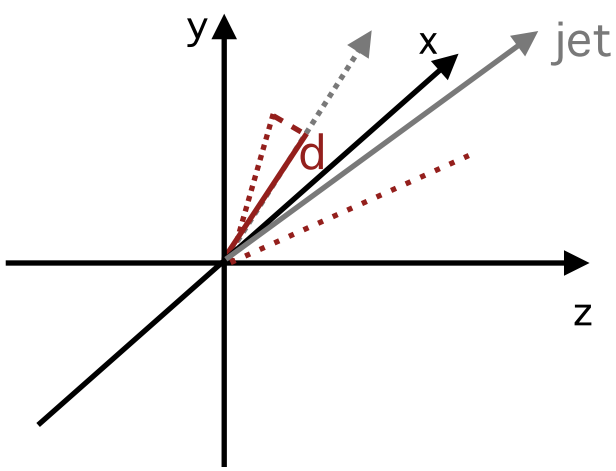

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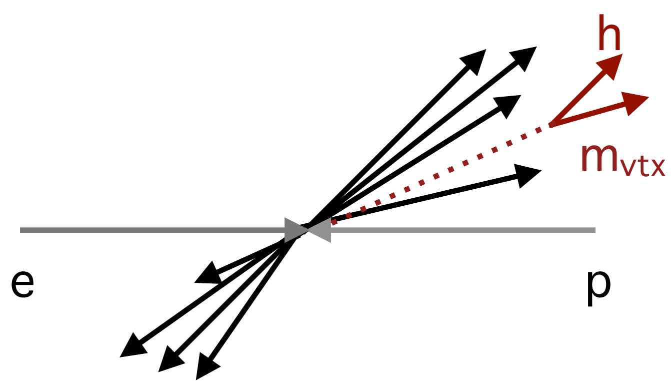

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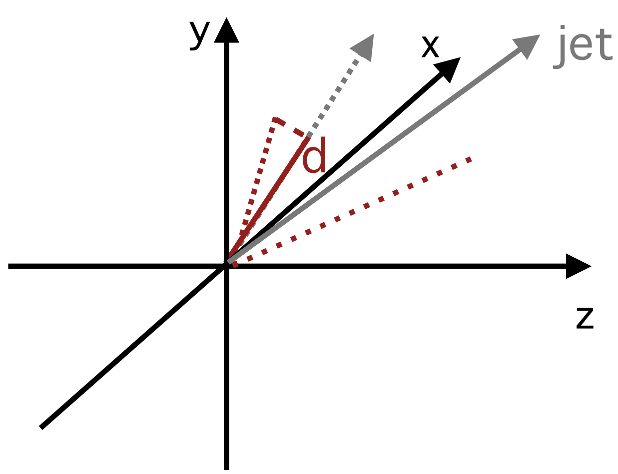
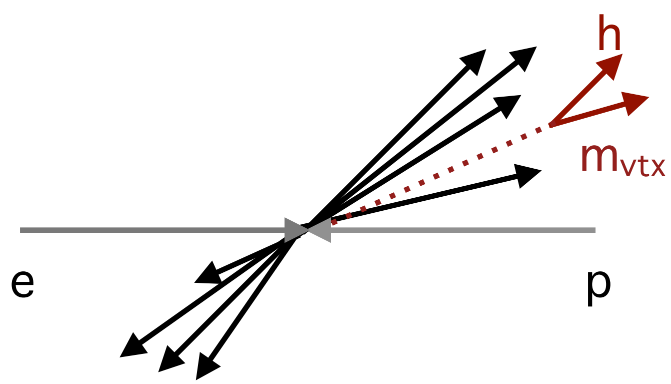


$S = \frac{d}{\delta d}$

Heavy-quark jets



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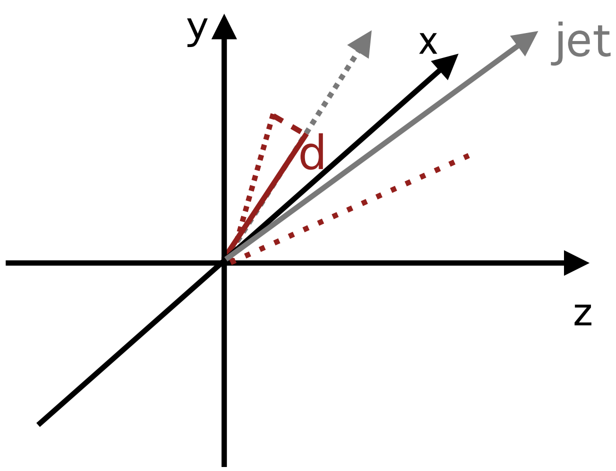

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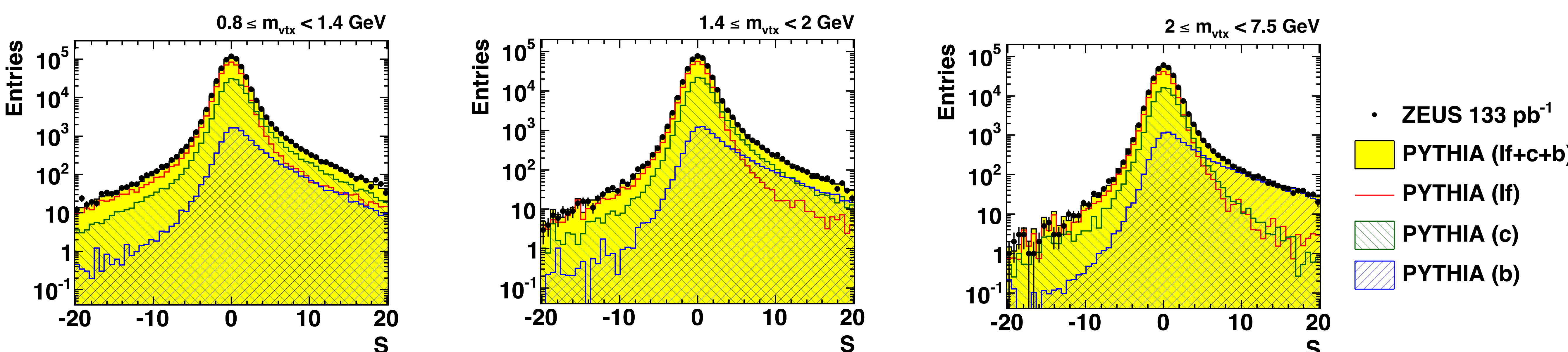
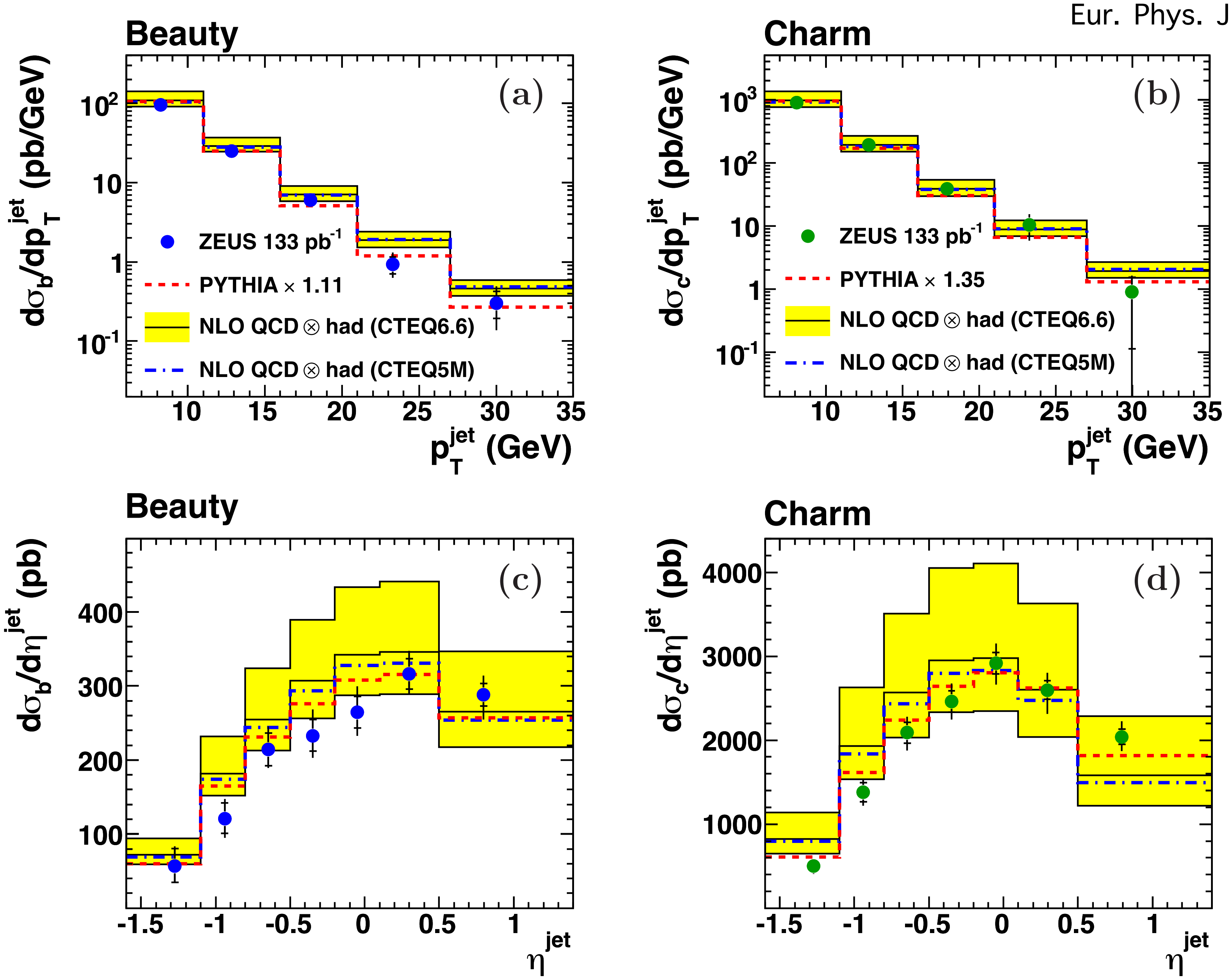


Heavy-quark jets results

Eur. Phys. J. C 71 (2011) 1659



- FMNR
  - NLO
  - massive scheme
  - proton PDF: CTEQ6.6/CTEQ5M
  - photon PDF: GRV-G HO
- scaled PYTHIA:
  - LO
  - collinear factorisation
  - direct+resolved
  - massive scheme
  - proton PDF: CTEQ4L&5L
  - photon PDF: GRV-G LO

p_T at parton level

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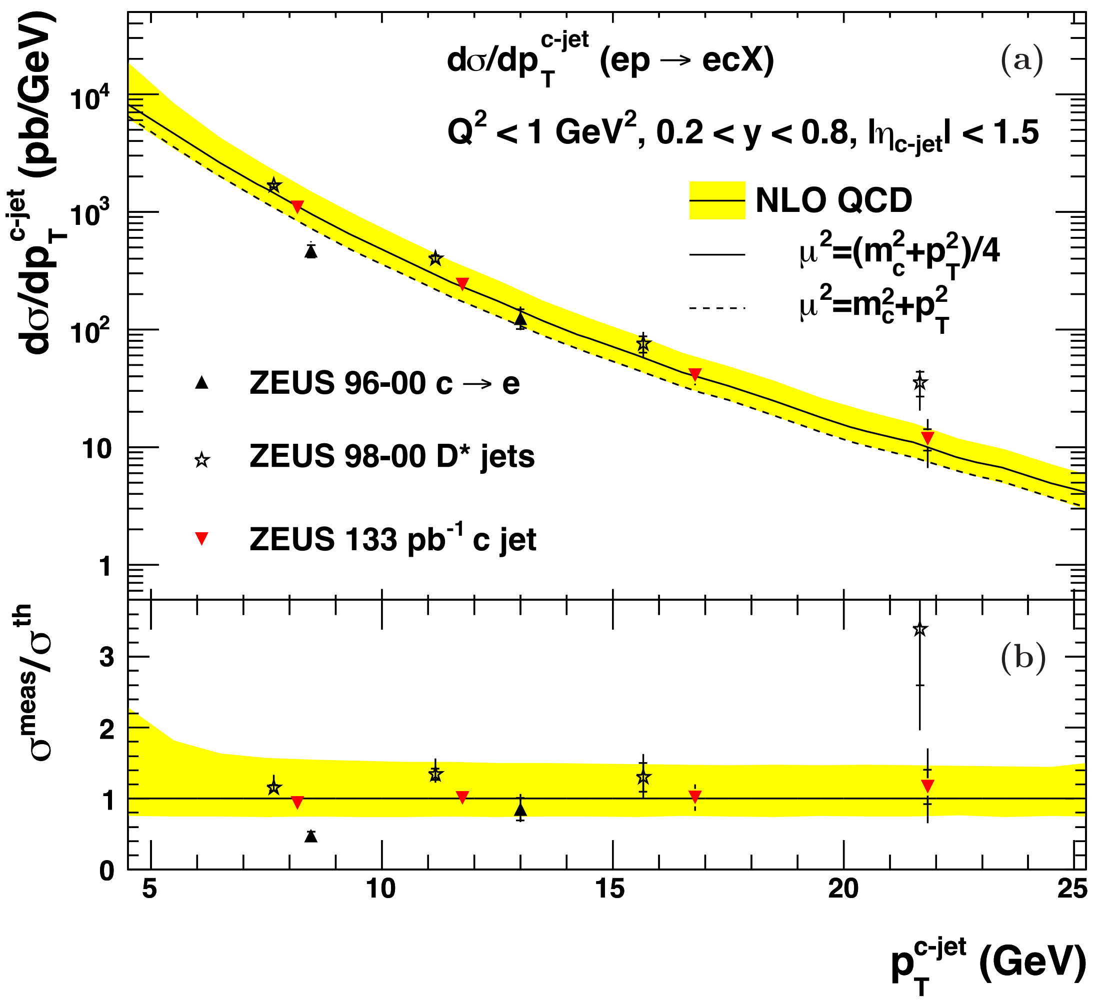

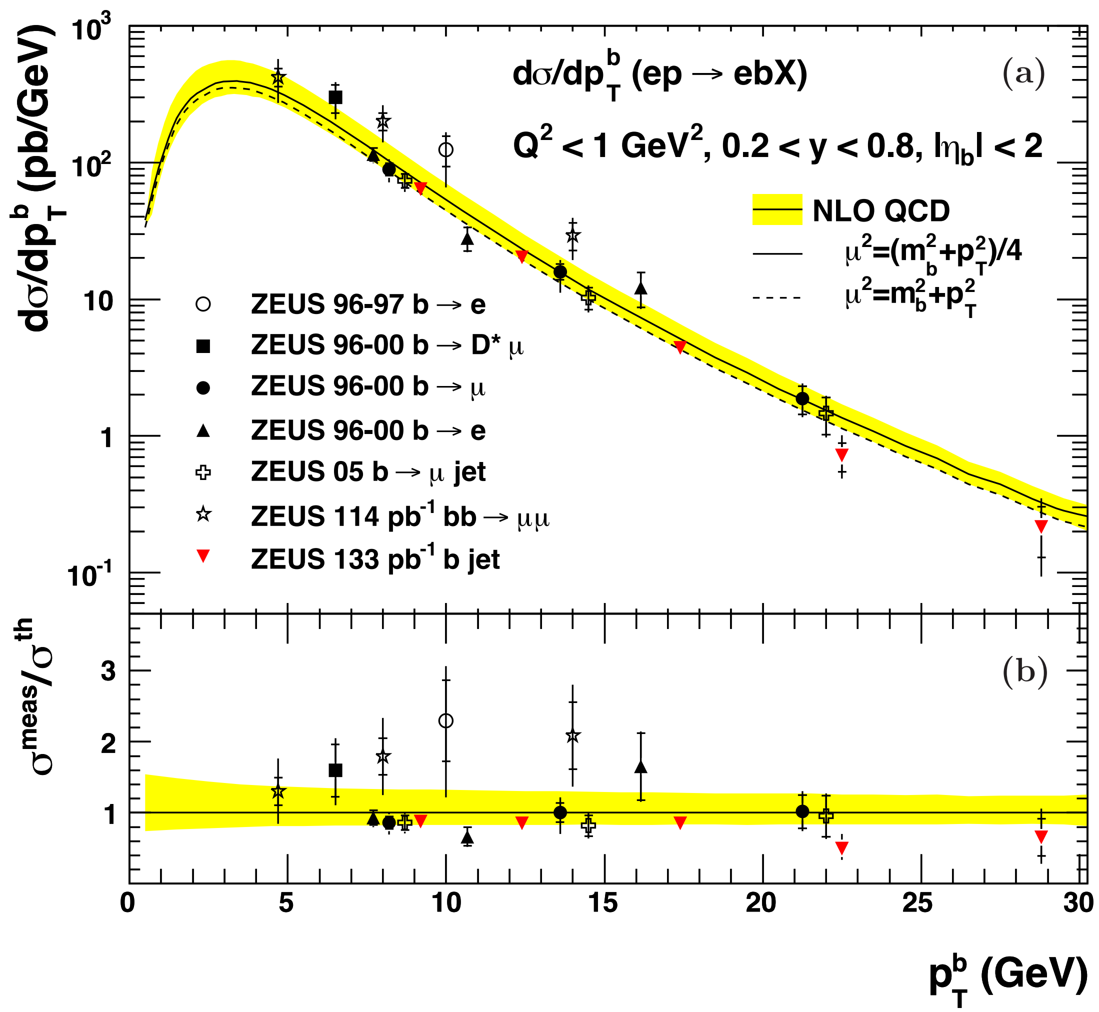

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Beauty photoproduction near threshold

$$ep \to e\underbrace{b\bar{b}}_{\to\, eeX'}X$$

Beauty photoproduction near threshold

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★ access to lower b-quark P_T than for jets and double-tags with muons

★ $P_T(b) \simeq 0$ → only hard scale = b-quark mass m_b

Beauty photoproduction near threshold

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- selection:
  - 2 e of either charge combination with $P_T(e)$ down to ~ 1 GeV
  - suppression of DIS events
  - enriched sample of isolated e

$$Q^2 \leq 1\ \mathrm{GeV}^2 \qquad |\eta(b)|,\ |\eta(\bar{b})| \leq 2$$
$$\sqrt{s} = 320\ \mathrm{GeV} \qquad 0.05 \leq y \leq 0.65$$

Beauty photoproduction near threshold

$$ep \to e\underbrace{b\bar{b}}_{\to\, eeX'}X$$

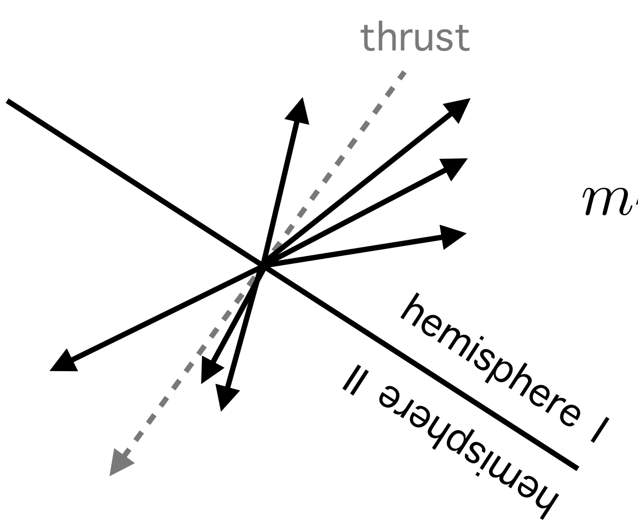
★ access to lower b-quark P_T than for jets and double-tags with muons

★ $P_T(b) \simeq 0$ → only hard scale = b-quark mass m_b

- selection:
  - 2 e of either charge combination with $P_T(e)$ down to ~ 1 GeV
  - suppression of DIS events
  - enriched sample of isolated e

$$Q^2 \leq 1\ \mathrm{GeV}^2 \qquad |\eta(b)|,\ |\eta(\bar{b})| \leq 2$$
$$\sqrt{s} = 320\ \mathrm{GeV} \qquad 0.05 \leq y \leq 0.65$$

- reconstruction of average $P_T(b)$ via hadronic final states:



$$m_T(b) = \sqrt{m_b^2 + \langle P_T(b)\rangle^2}$$
$$\approx \frac{\alpha}{2}\left(\sum_{hemiI} \vec{P}_{T,i} + \sum_{hemiII} \vec{P}_{T,i}\right)$$

Beauty photoproduction near threshold

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$$\hookrightarrow eeX'$$

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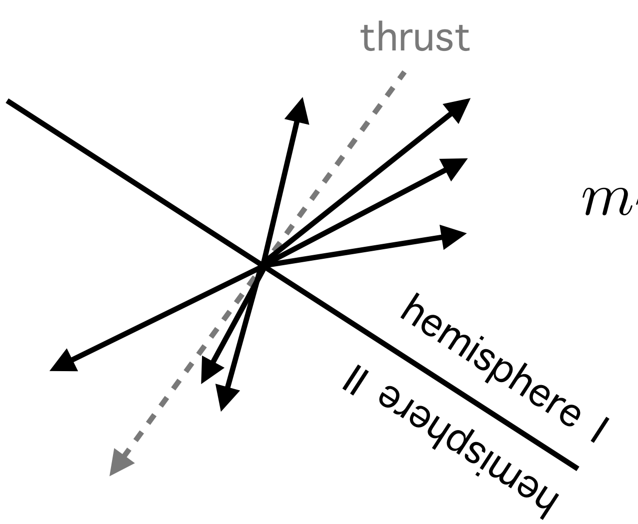

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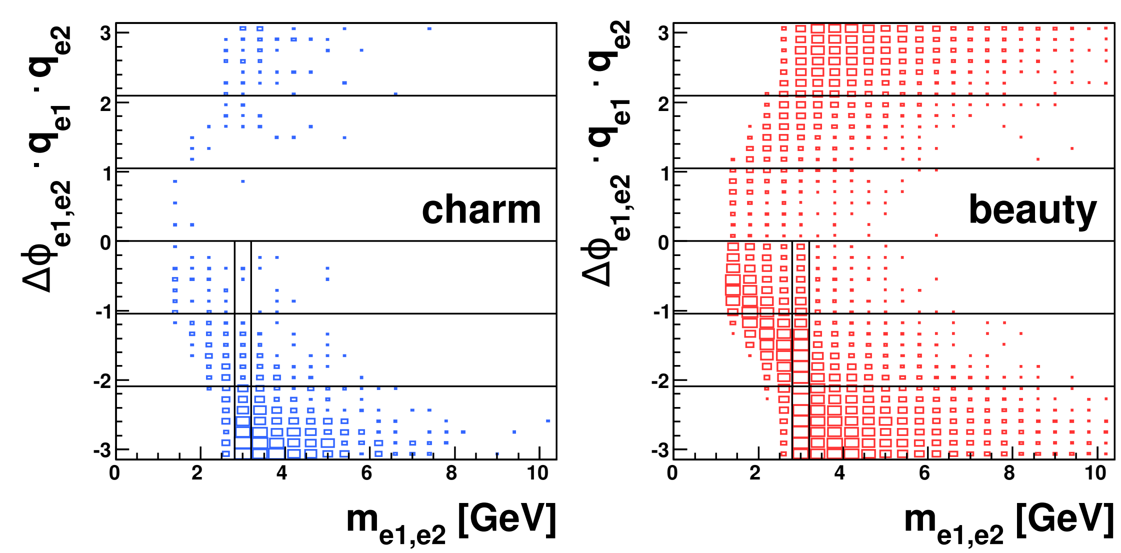
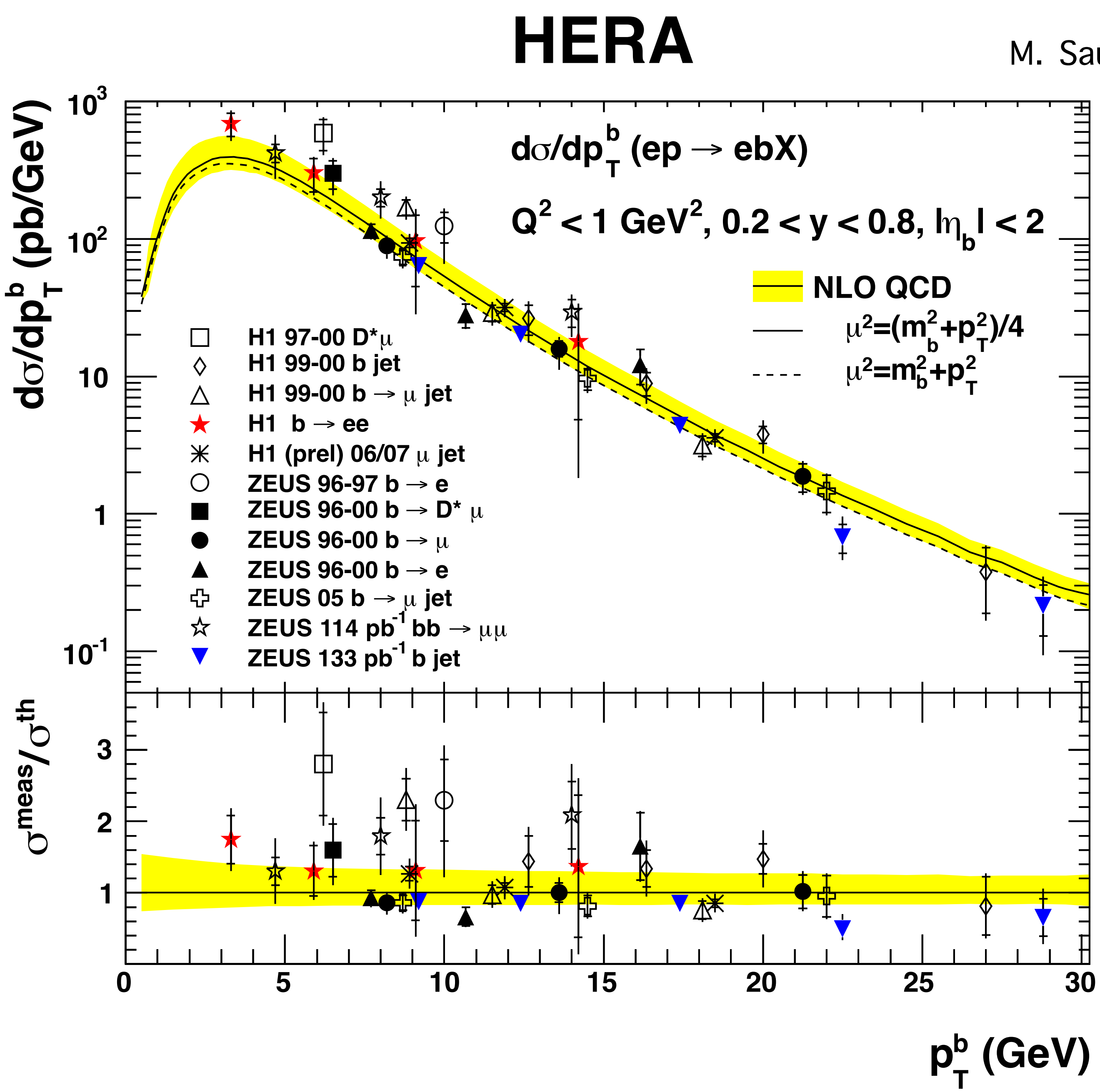
$$\approx \frac{\alpha}{2}\left(\sum_{hemiI} \vec{P}_{T,i} + \sum_{hemiII} \vec{P}_{T,i}\right)$$

- separation of uds, charm and J/ψ background via:
  - different e selection criteria (uds)
  - m_{e1e2}, $|\phi_{e1}-\phi_{e2}|$ and e charge (charm, J/ψ)



Beauty near-threshold results

M. Sauter, Pos(ICHEP2012)283

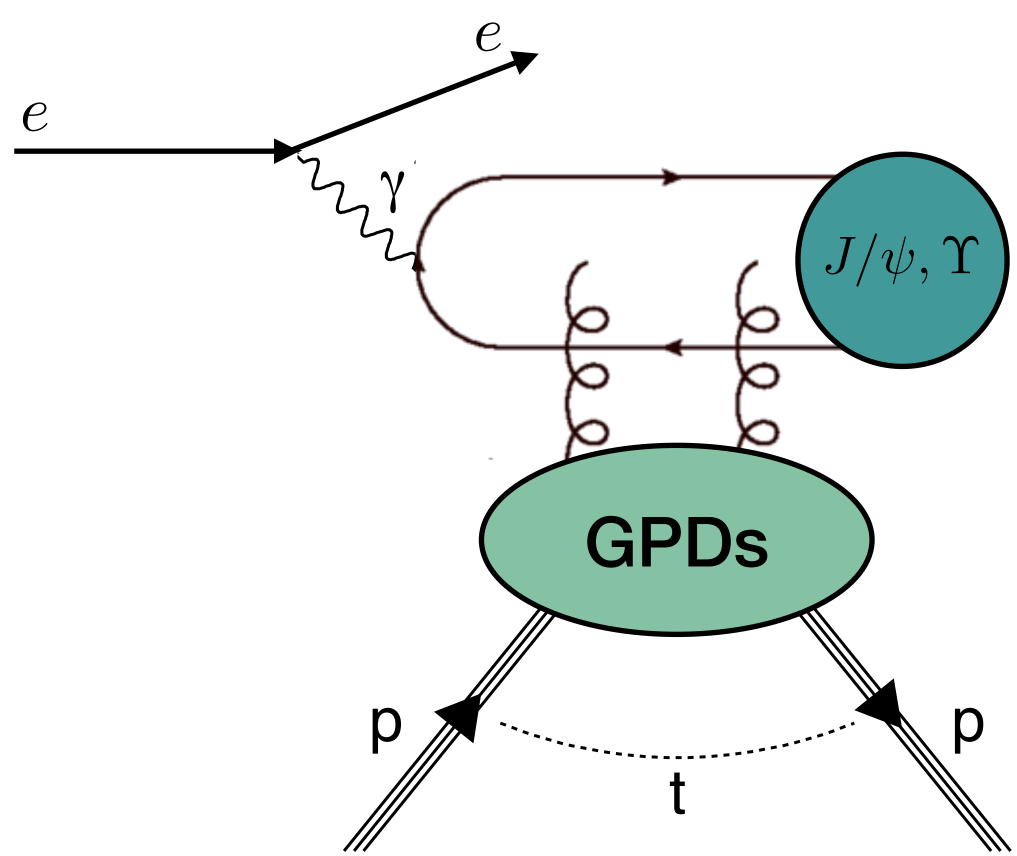


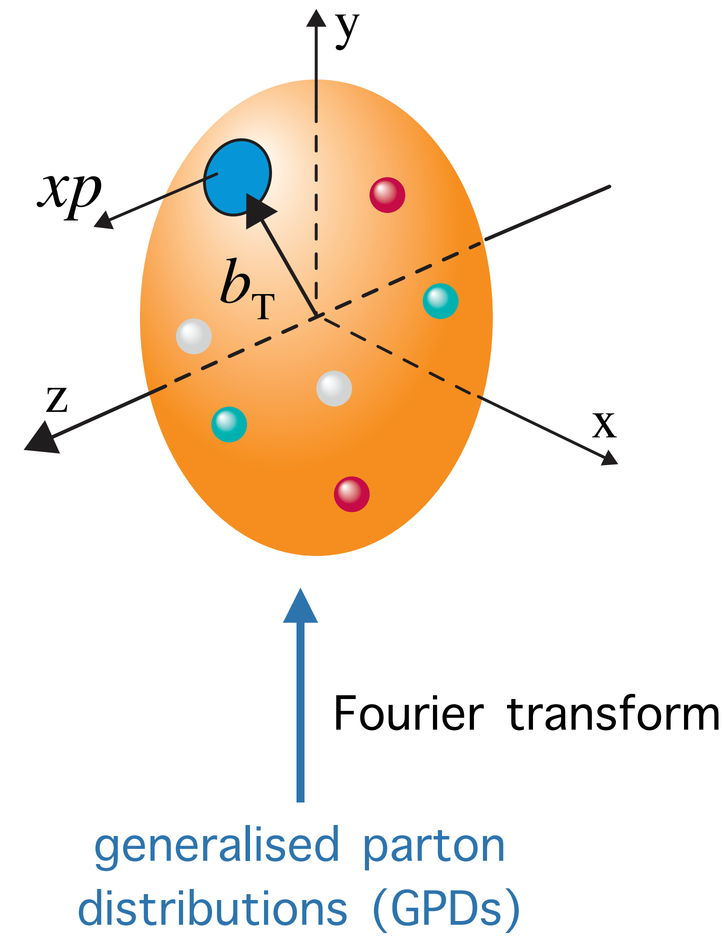
Eur. Phys. J. C 72 (2012) 2148

Eur. Phys. J. C 71 (2011) 1659

- FMNR
  - NLO
  - massive scheme

Exclusive processes





Exclusive meson photoproduction

hard scale = large quark mass

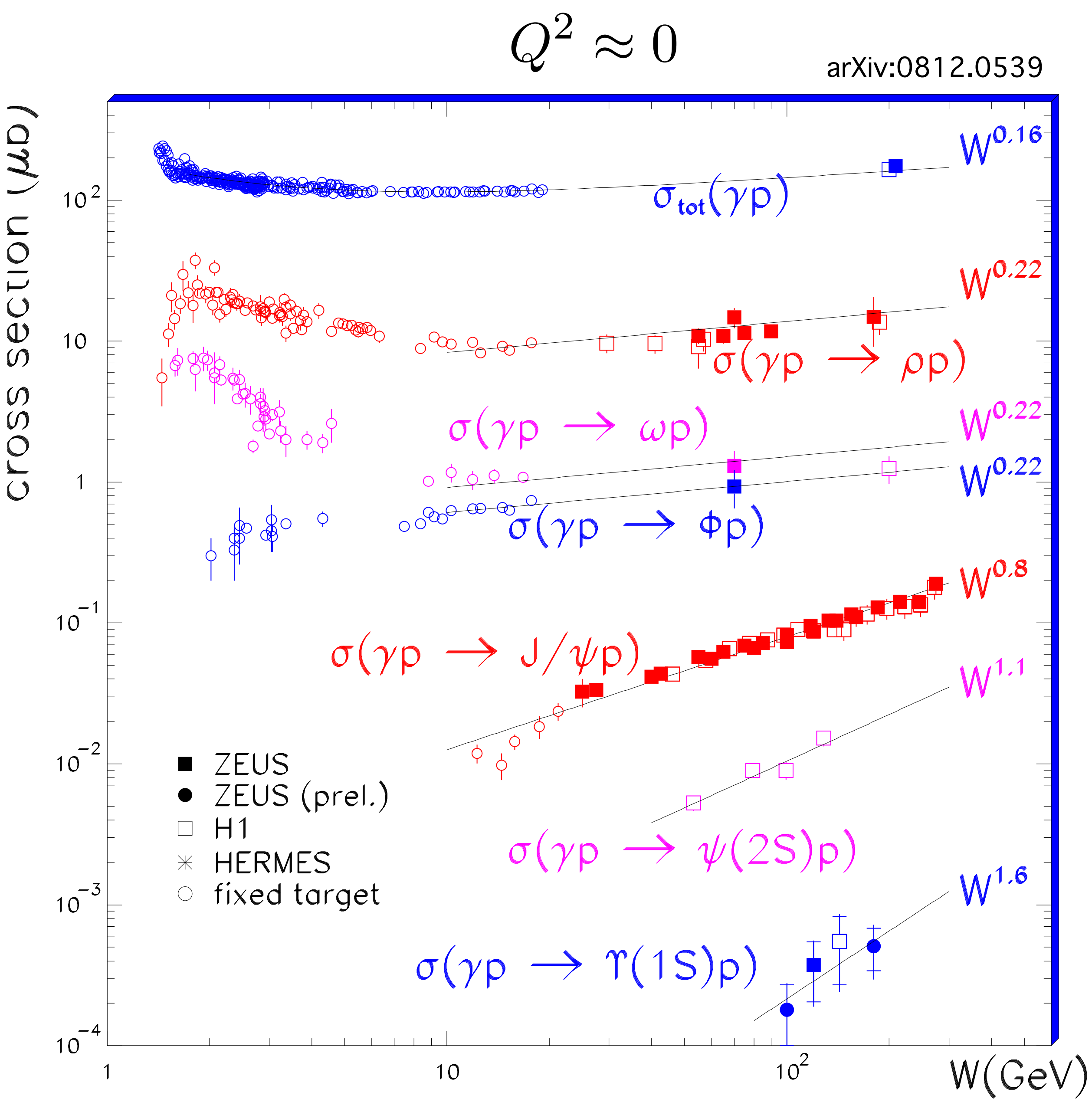
H1 – EPJ C 46 ('06) 585; 73 ('13) 2466; PLB 541 ('02) 251

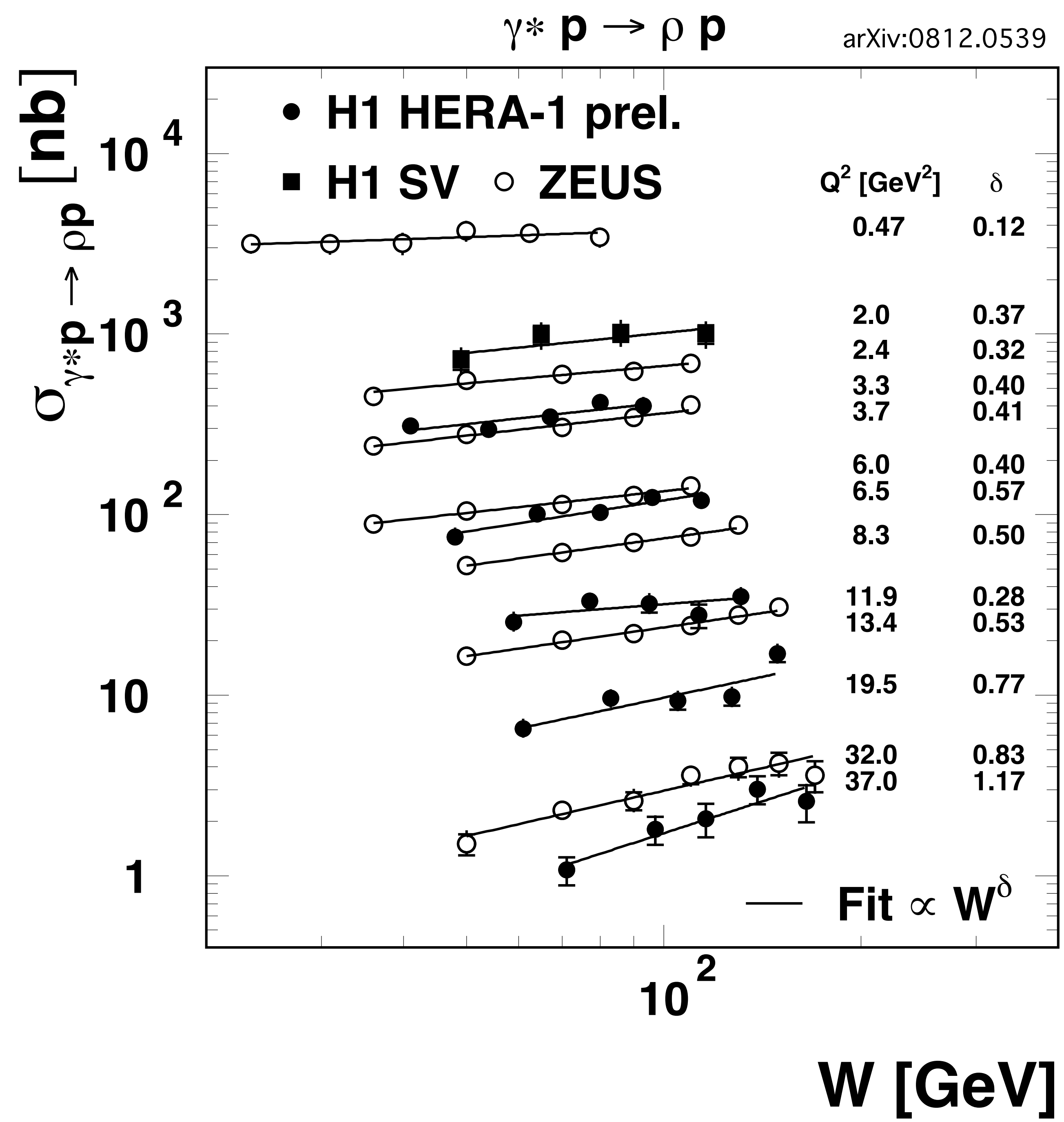
ZEUS – Nucl. Phys. B 695 ('04) 3; PLB 680 ('09) 4

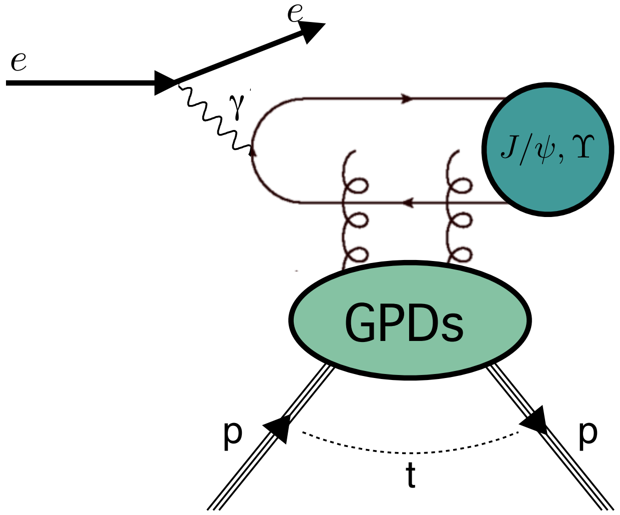
$$W_{\gamma p} = [30, 300]\ \mathrm{GeV}$$

$$10^{-4} \leq x \leq 10^{-2}$$

W dependence



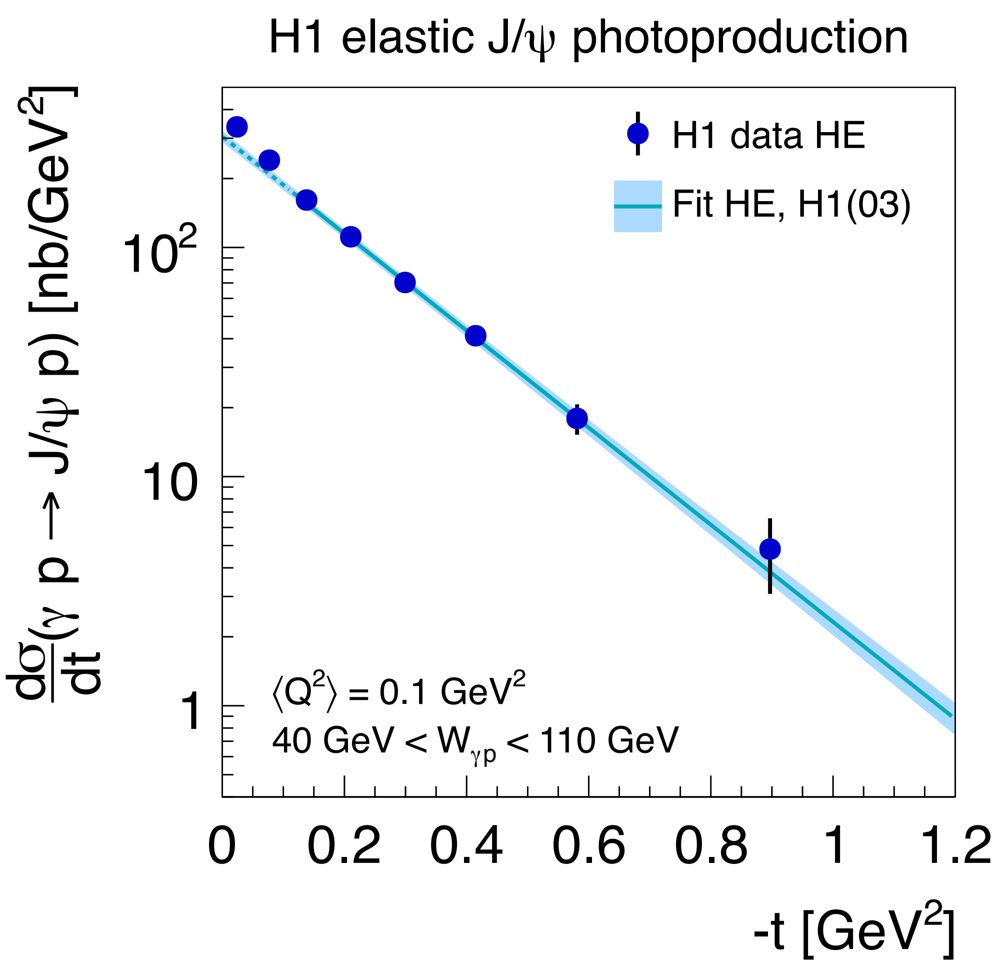


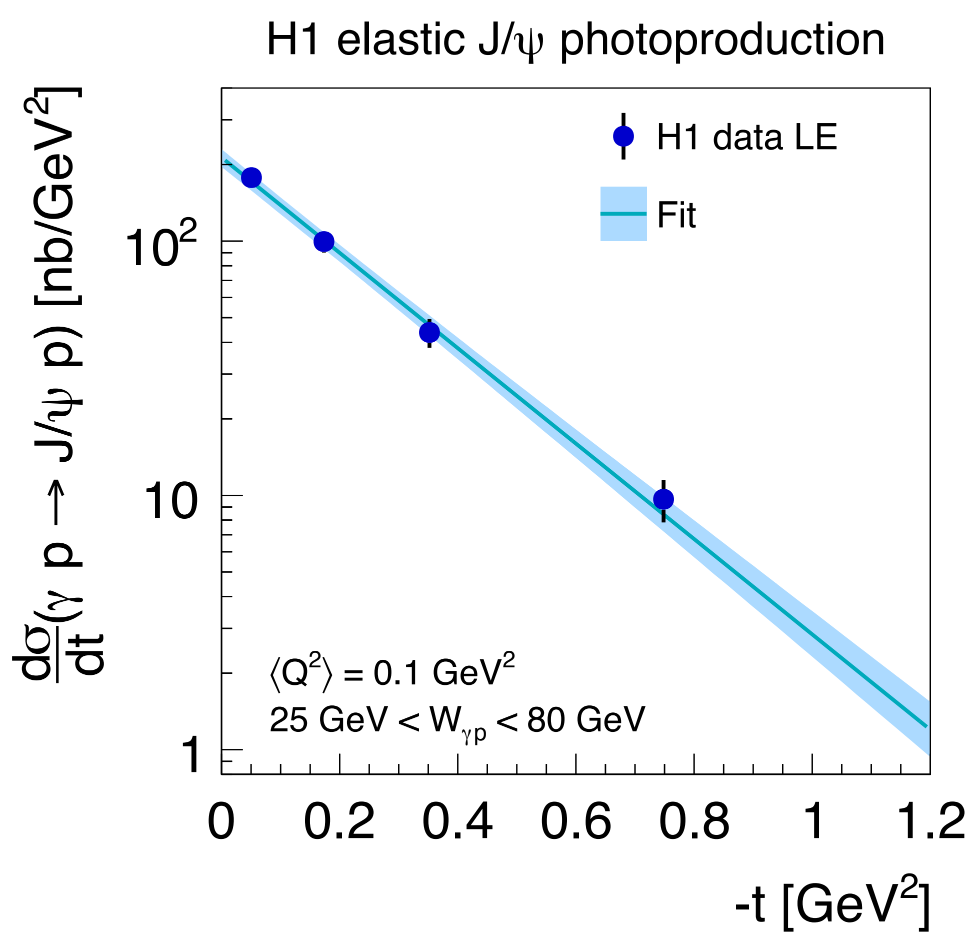


t slope

elastic

Eur. Phys. J. C73 (2013) 2466

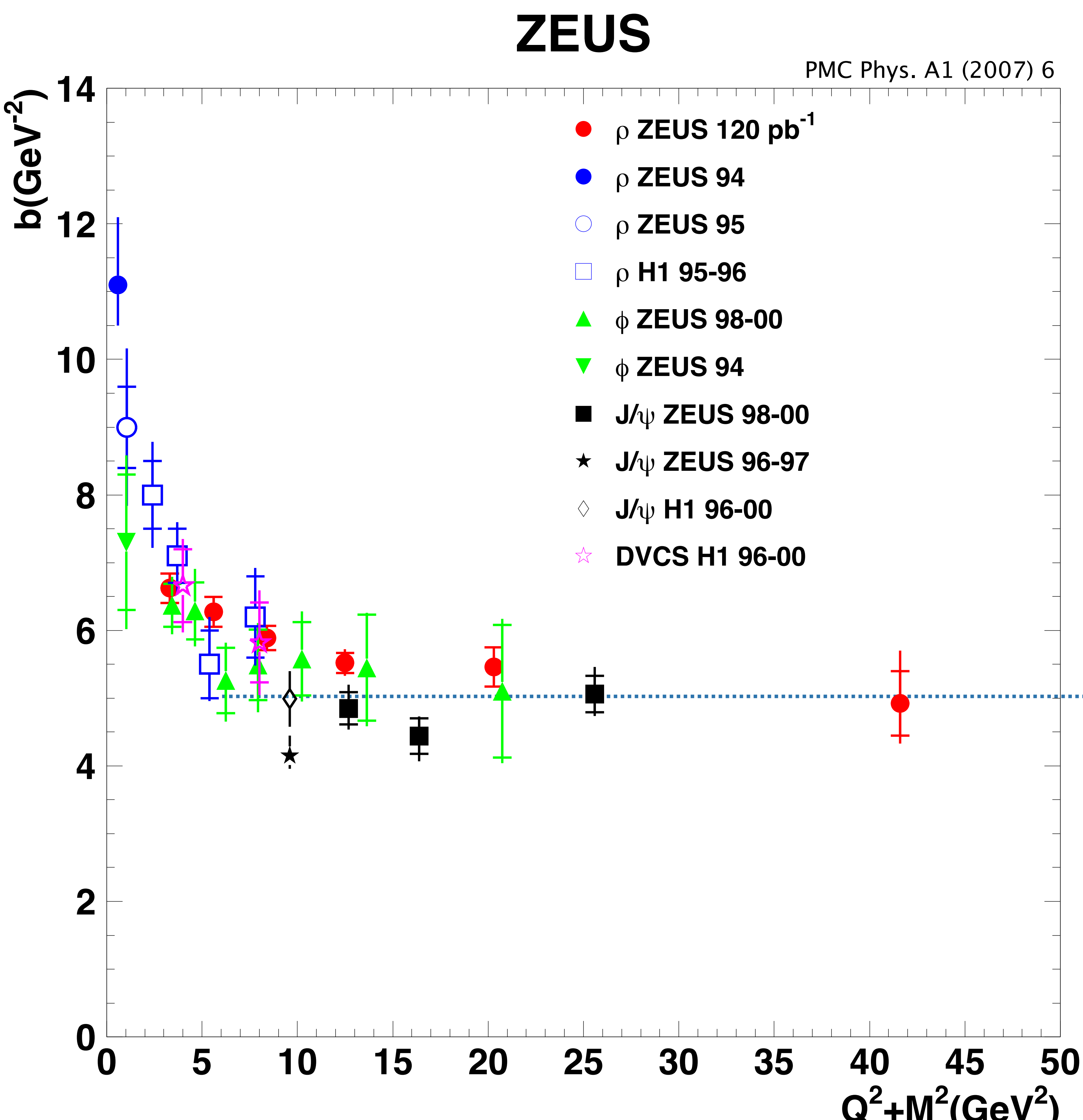




$$b = 4.88 \pm 0.15\ \mathrm{GeV}^{-2}$$

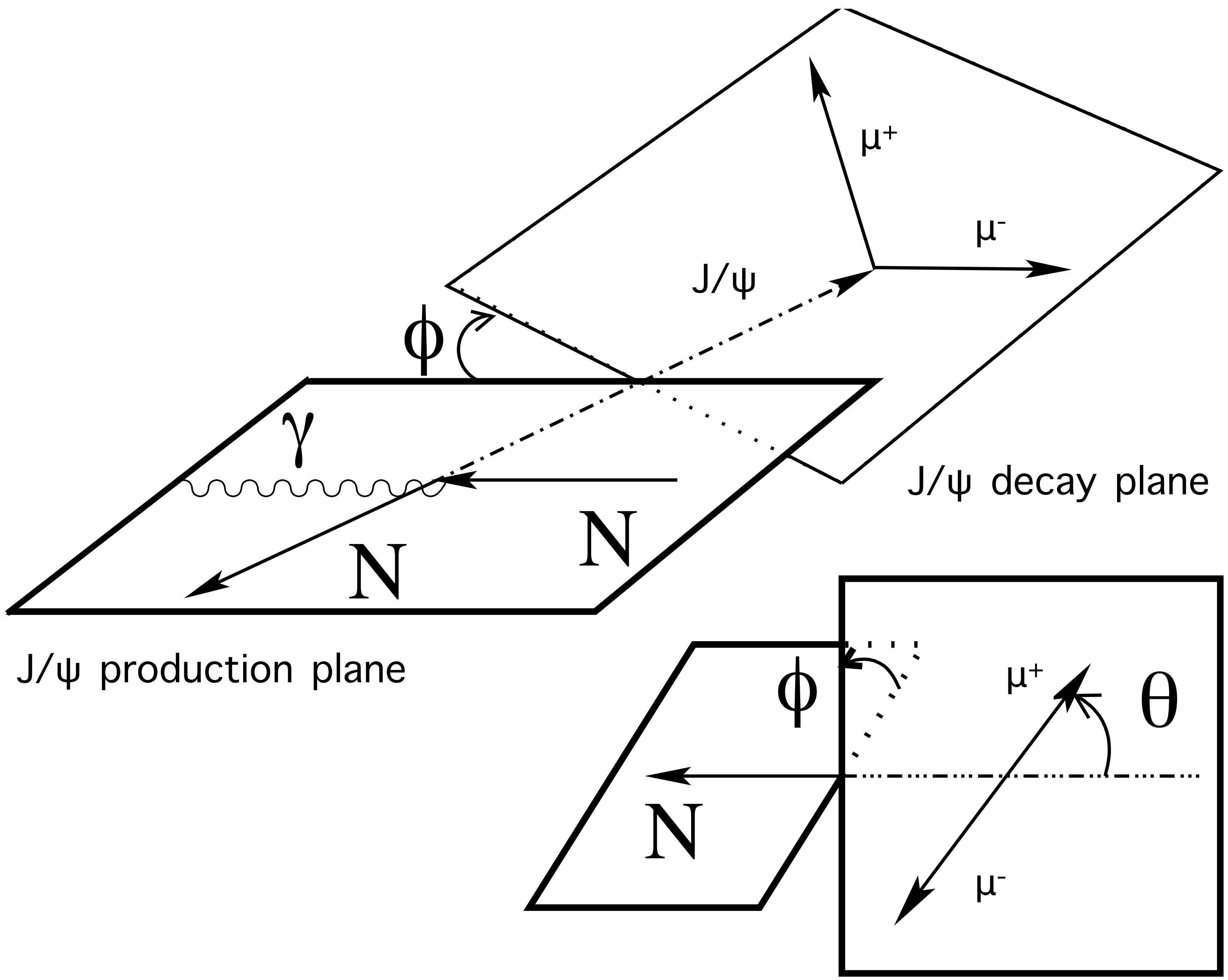
$$b = 4.30 \pm 0.20\ \mathrm{GeV}^{-2}$$

Q^2+M^2 dependence of b



$5\ \mathrm{GeV}^2:\ \langle r \rangle_g \sim 0.6\ \mathrm{fm}$

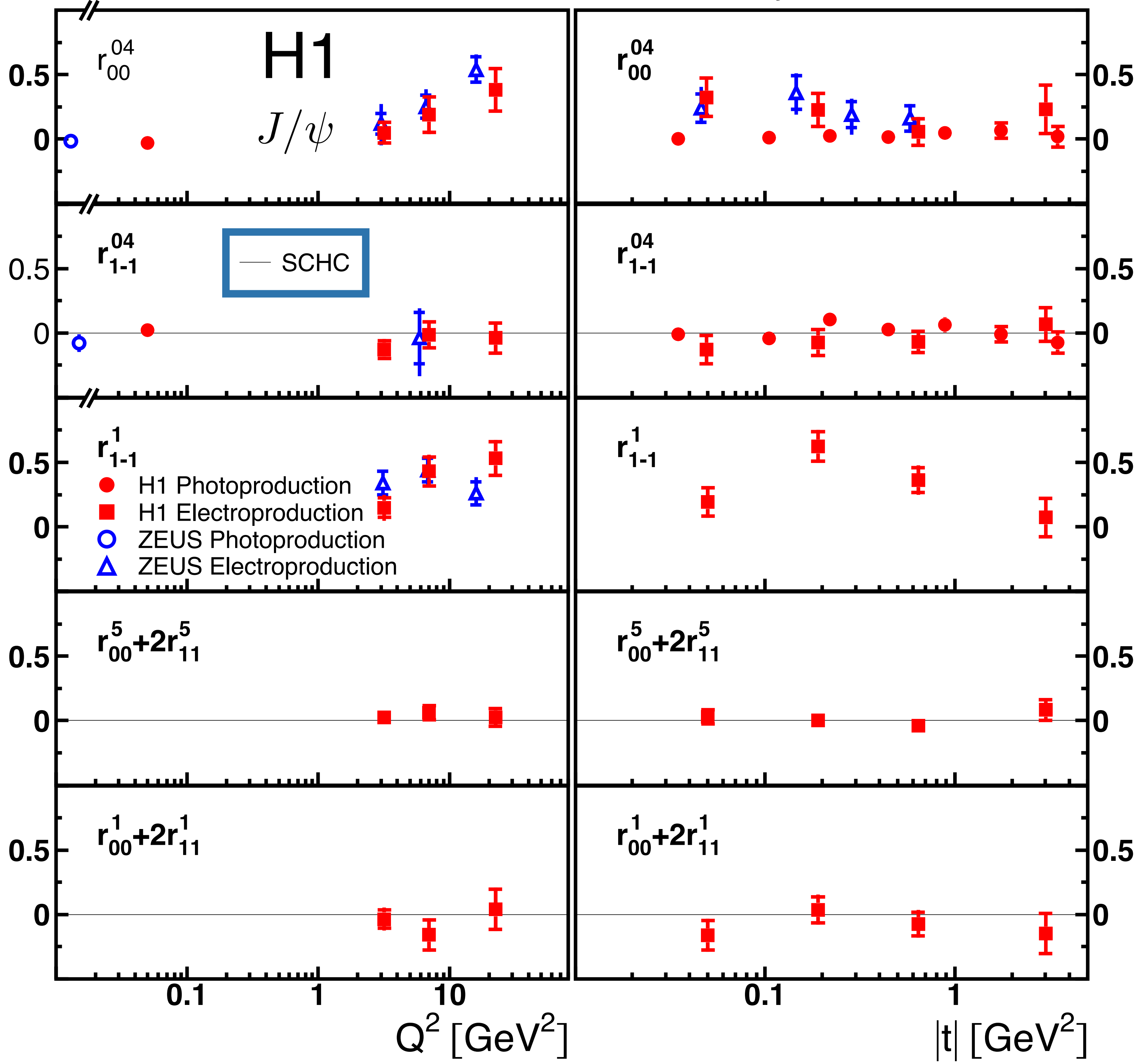
Angular distribution



Fit angular distribution of decay muons $\mathcal{W}(\phi, \theta)$ and extract either Spin Density Matrix Elements (SDMEs) or helicity amplitude ratios

SDMEs

Eur. Phys. J. C 46 (2006) 585-603

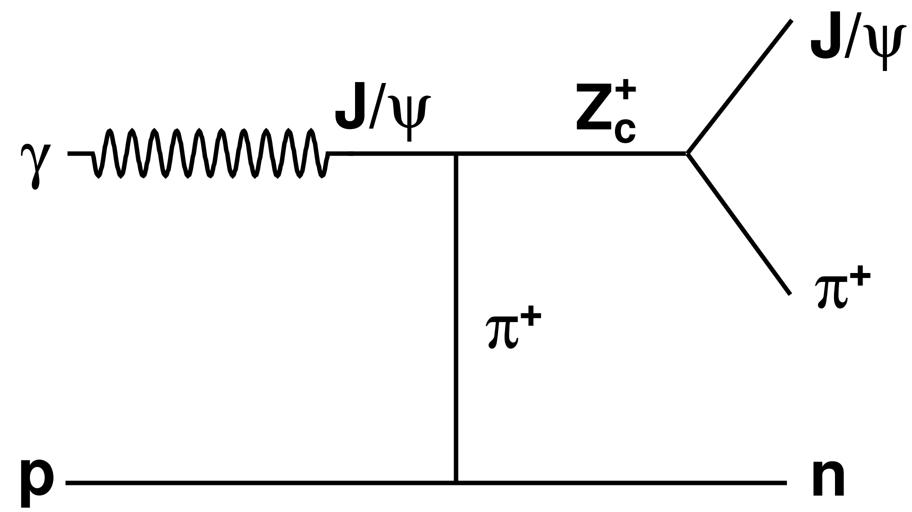


s-channel helicity conservation

Search for exclusive production of $Z_c^{\pm}(3900)$

COMPASS

PLB 742 (2015) 330–334

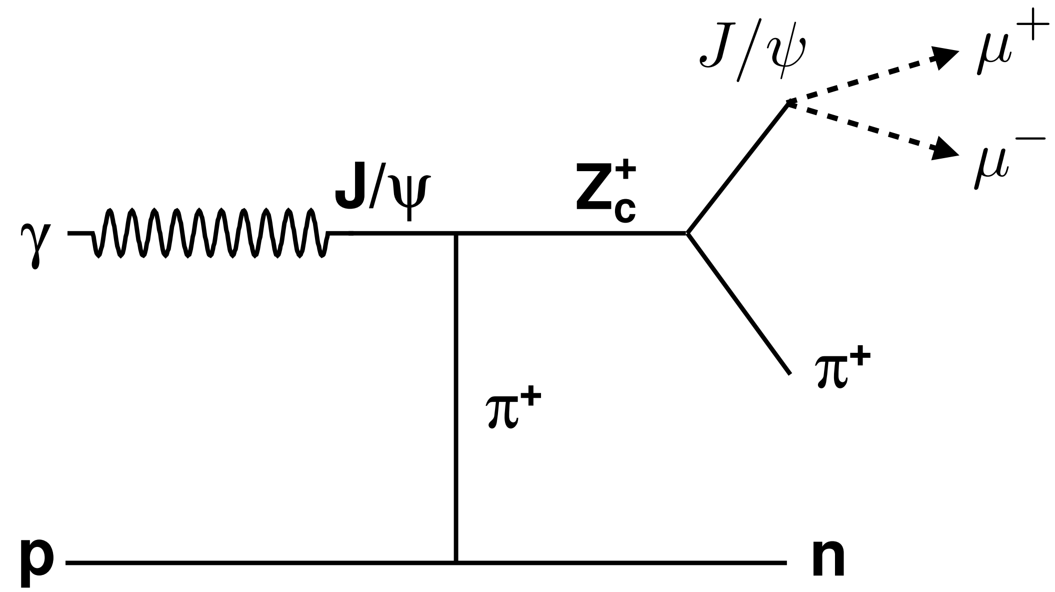


$\sqrt{s_{\gamma N}} = 7 - 19 \text{ GeV}$

$$\mu^+(160/200 \text{ GeV})N \rightarrow \mu^+ Z_c^{\pm}(3900)$$

Search for exclusive production of $Z_c^{\pm}(3900)$

PLB 742 (2015) 330–334



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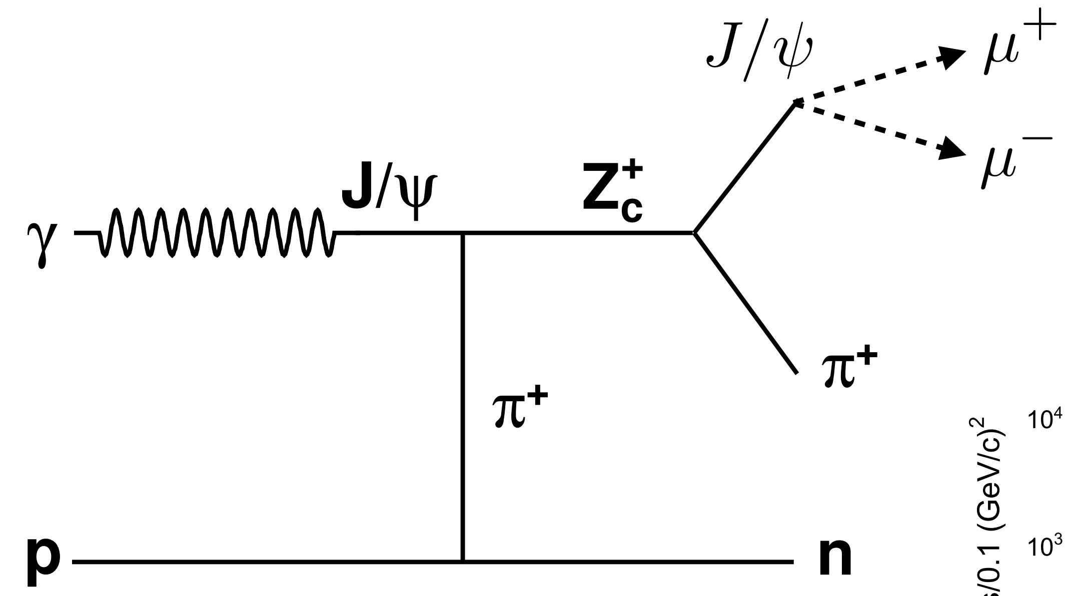
PLB 742 (2015) 330–334



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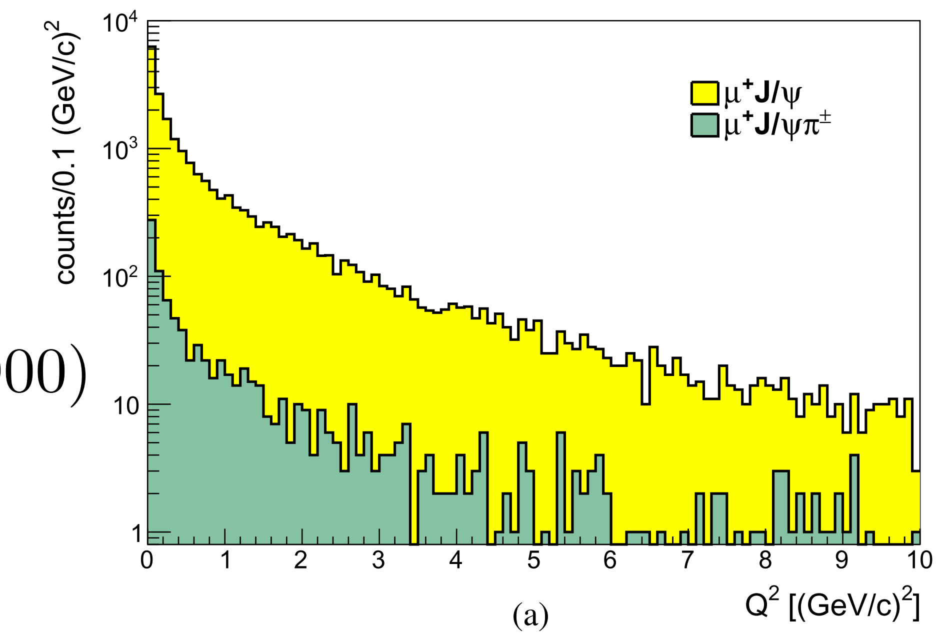
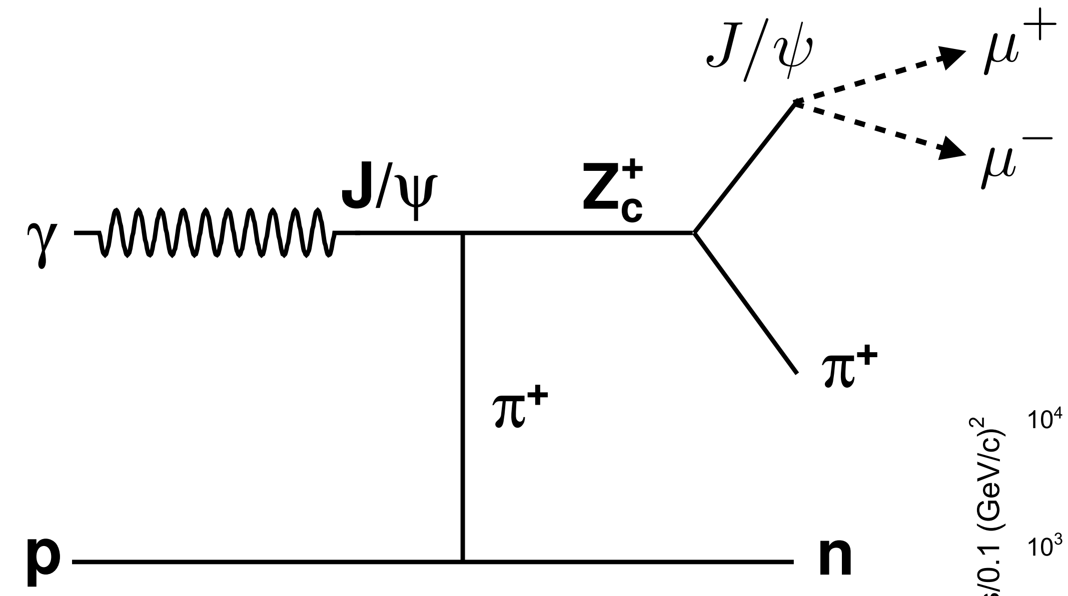


(a)

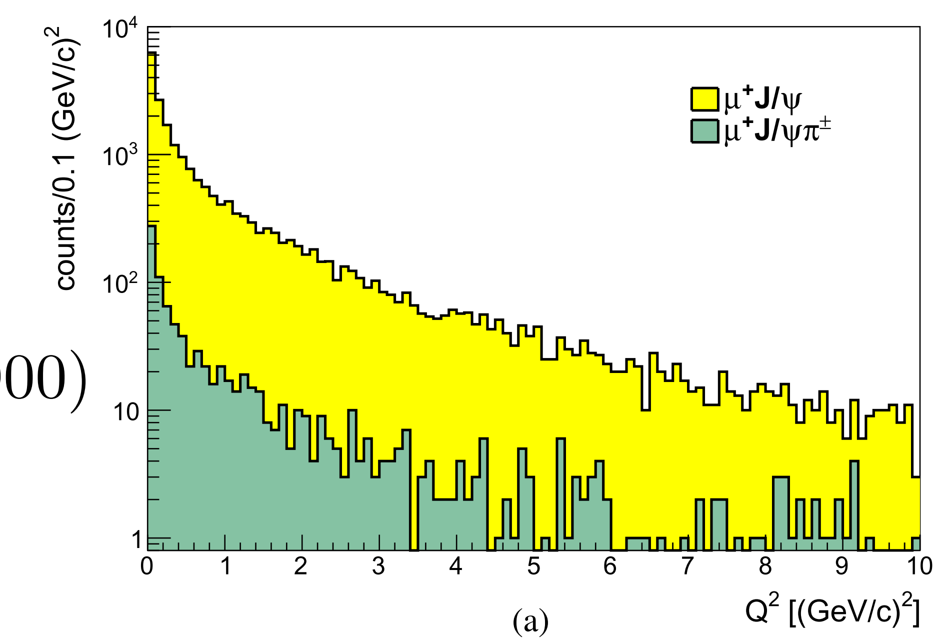
Search for exclusive production of $Z_c^{\pm}(3900)$

PLB 742 (2015) 330–334



$$\sqrt{s_{\gamma N}} = 7 - 19 \text{ GeV}$$

$$\mu^+(160/200 \text{ GeV})N \to \mu^+ Z_c^{\pm}(3900)$$

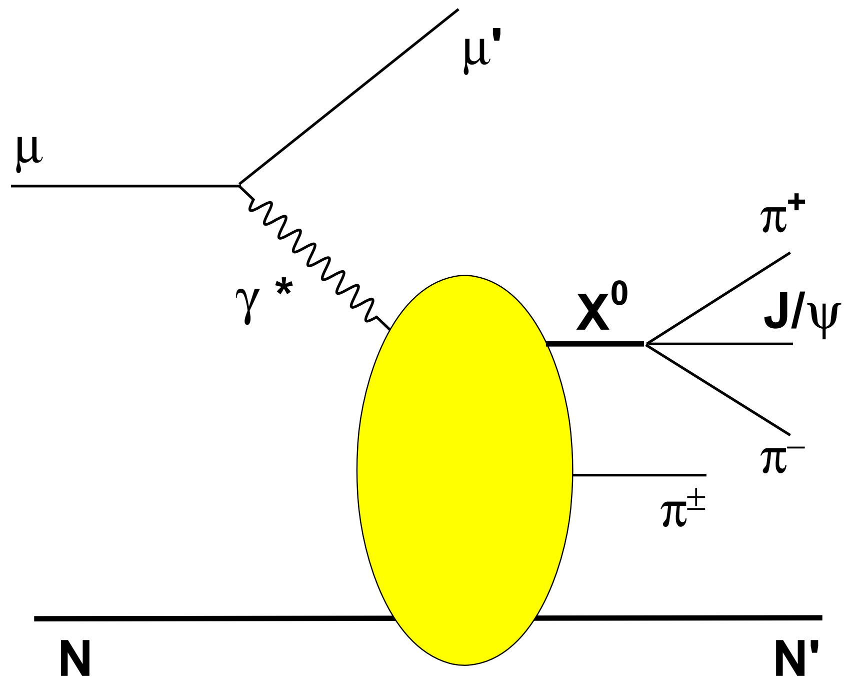


(a)

$$BR(Z_c^{\pm}(3900) \to J/\psi\pi^{\pm}) \times \sigma_{\gamma N \to Z_c^{\pm}(3900)N} / \sigma_{\gamma N \to J/\psi N} < 3.7 \times 10^{-3}$$

Search for exclusive production of X(3872)

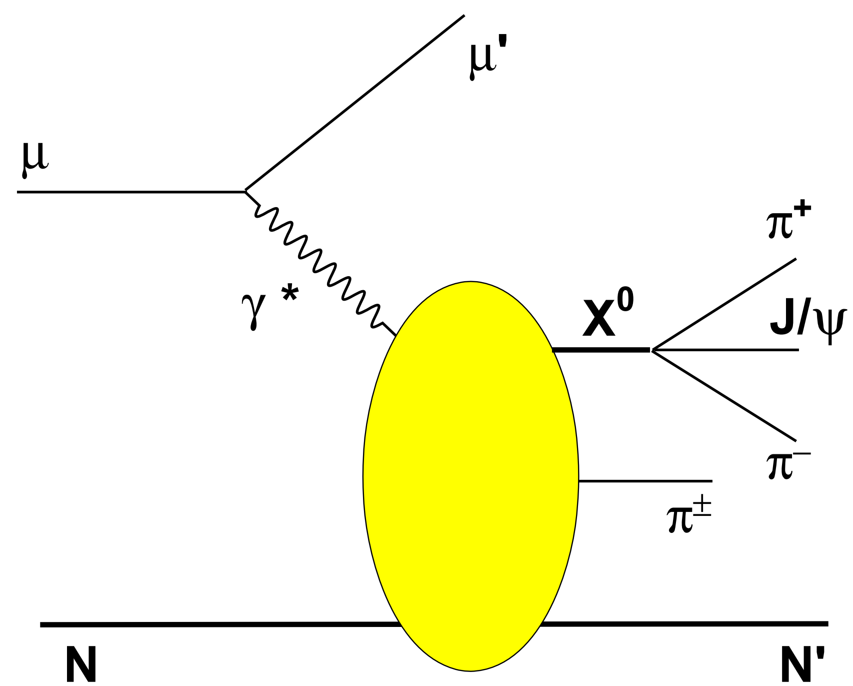
PLB 783 (2018) 334–340



$\sqrt{s_{\gamma N}} = 8 - 18 \text{ GeV}$

Search for exclusive production of X(3872)

PLB 783 (2018) 334–340



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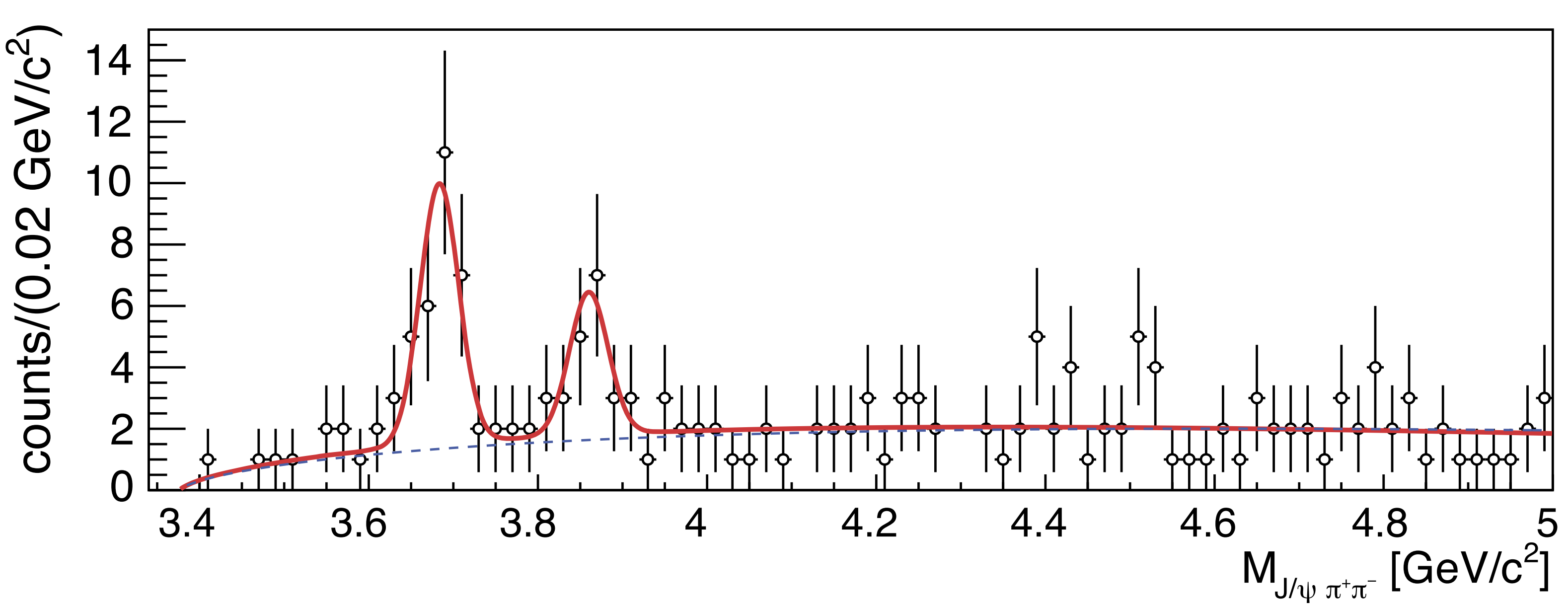

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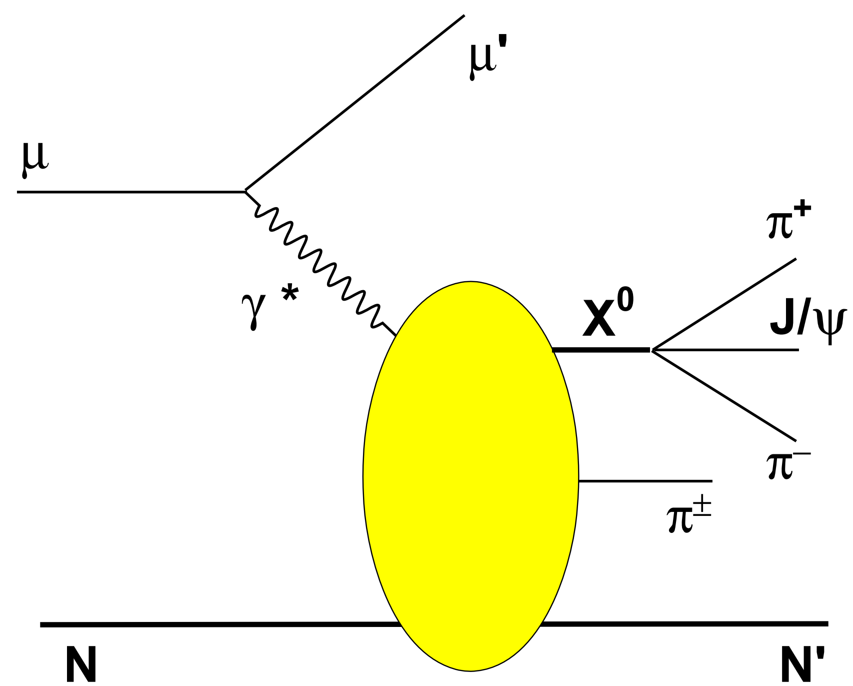
PLB 783 (2018) 334–340



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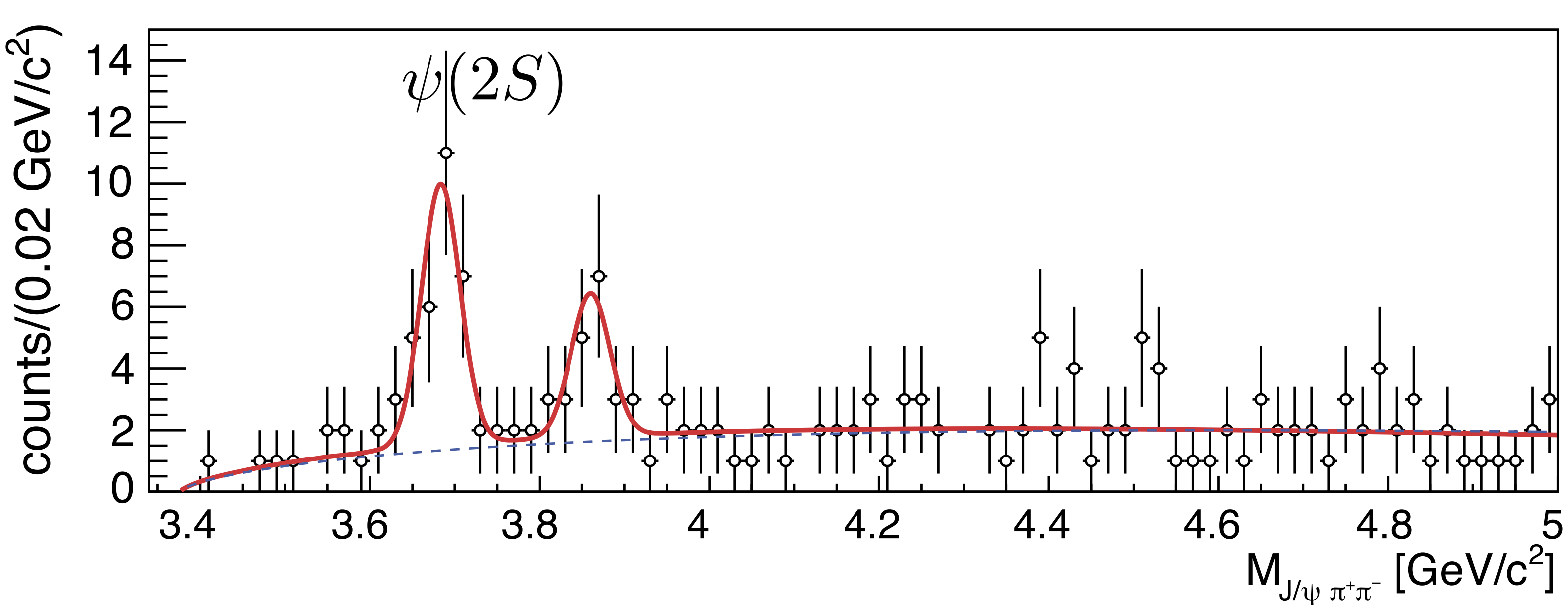

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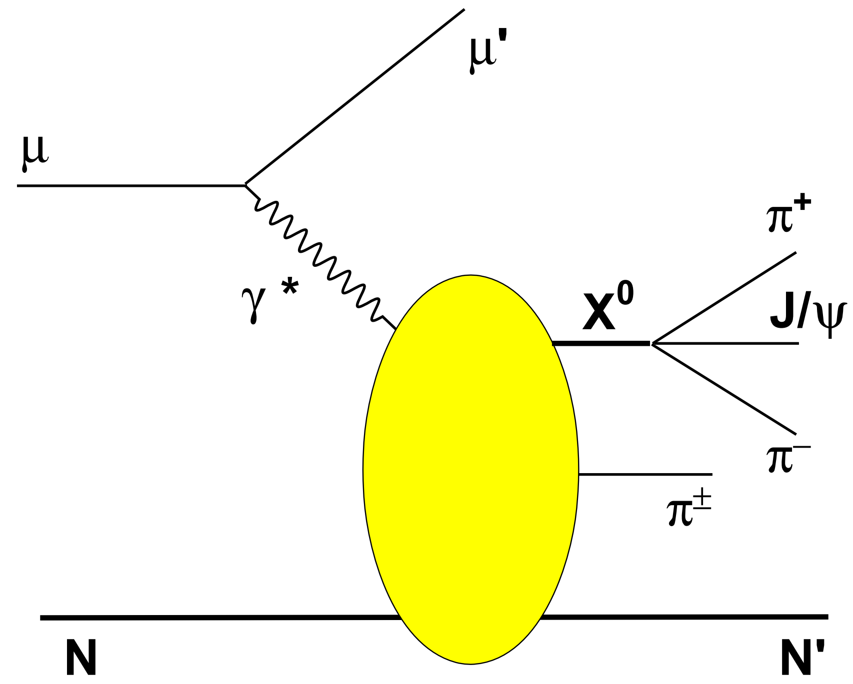
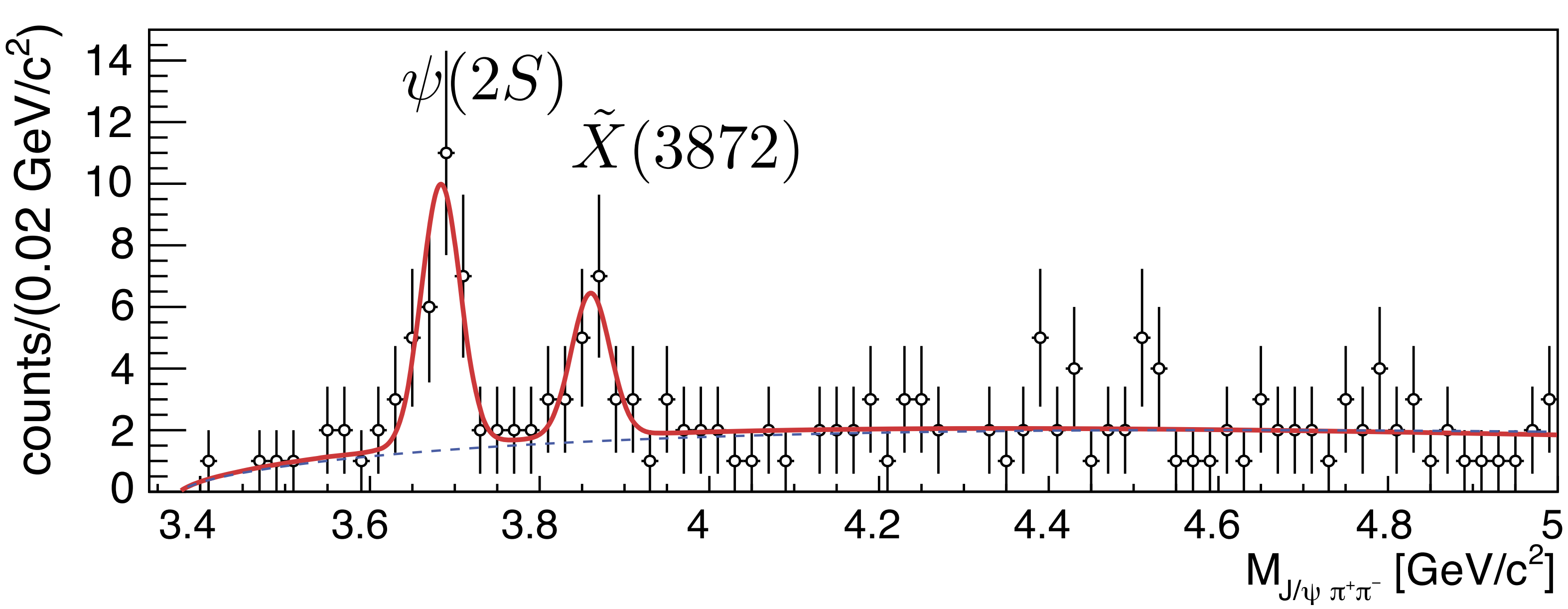
PLB 783 (2018) 334–340



$\sqrt{s_{\gamma N}} = 8 - 18$ GeV



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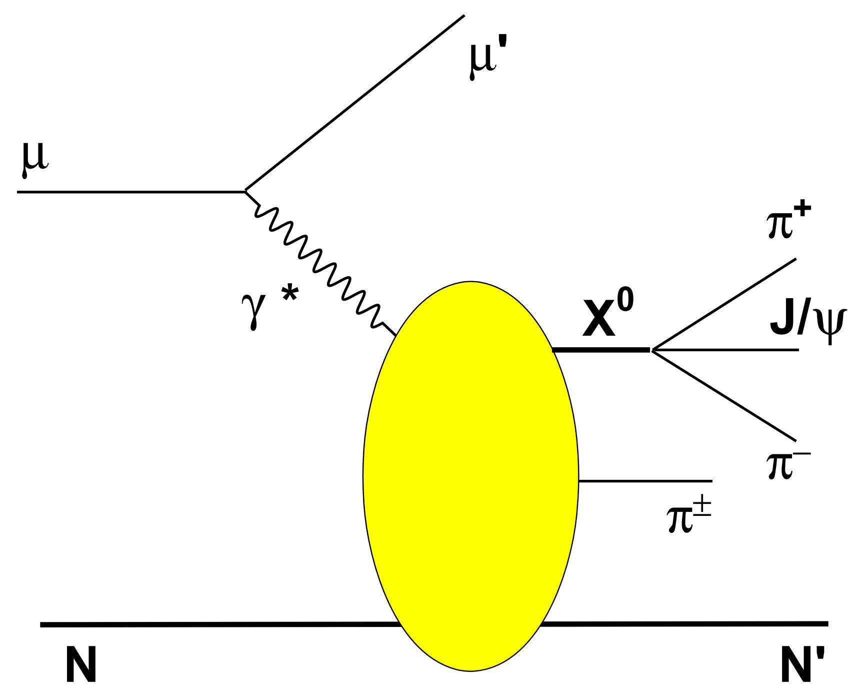

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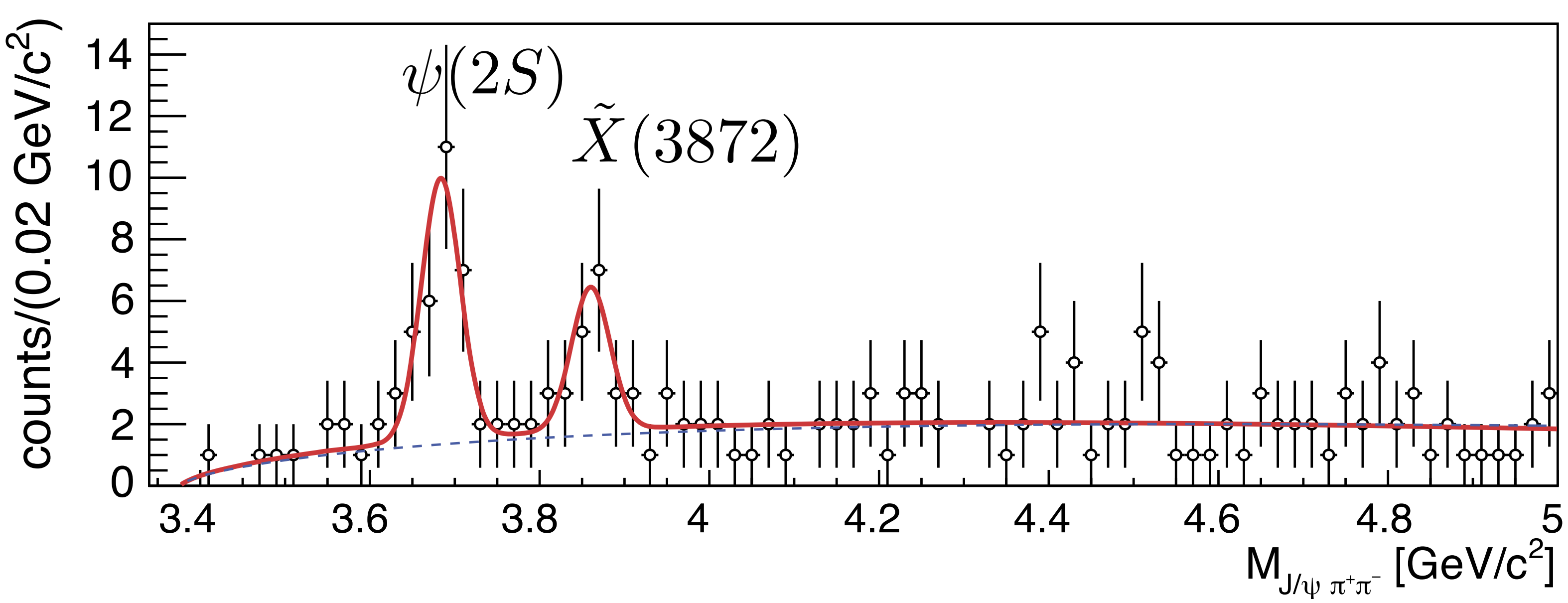

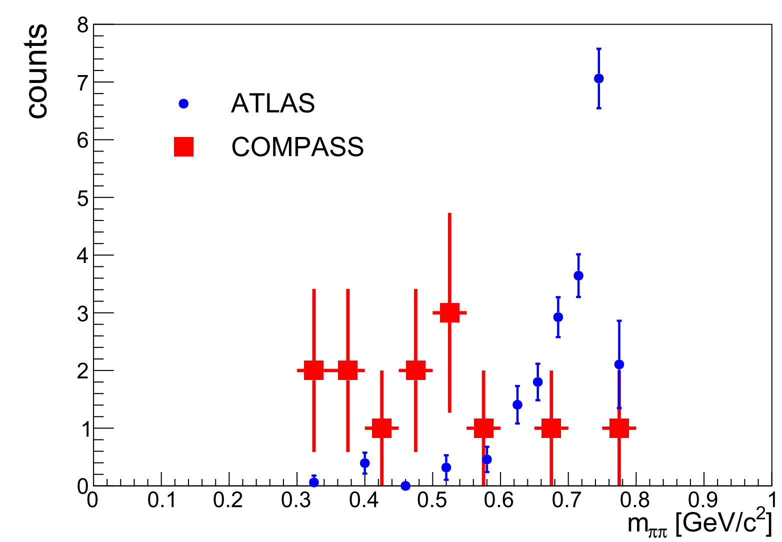

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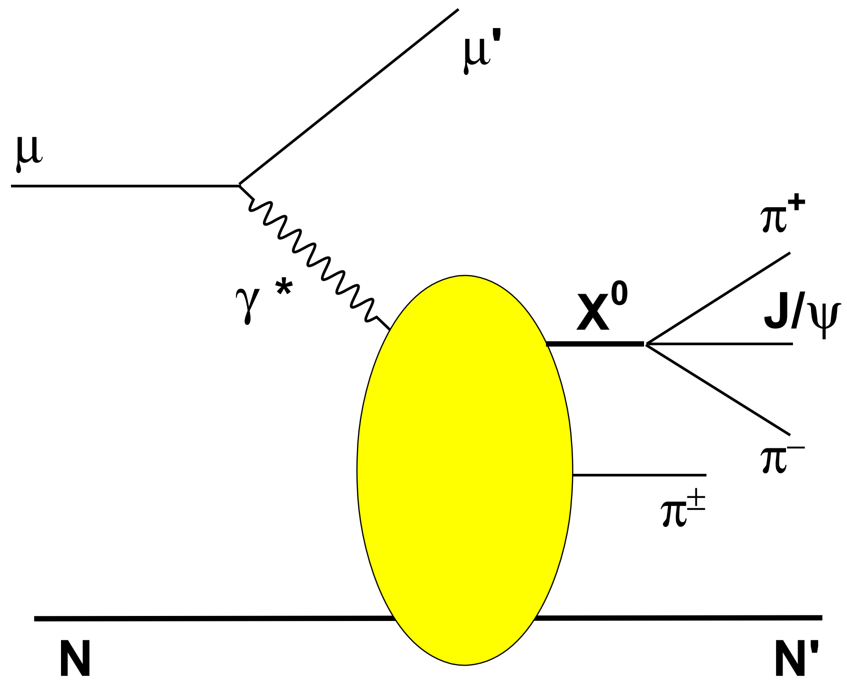
PLB 783 (2018) 334–340



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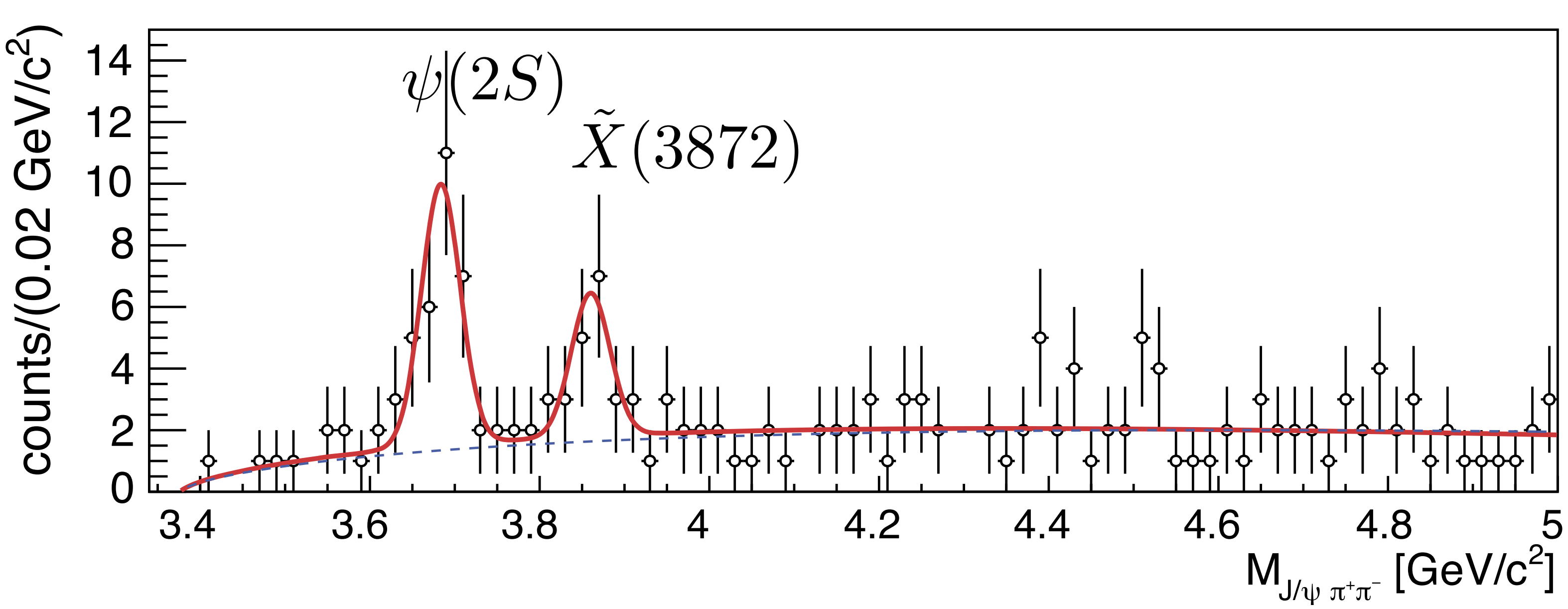
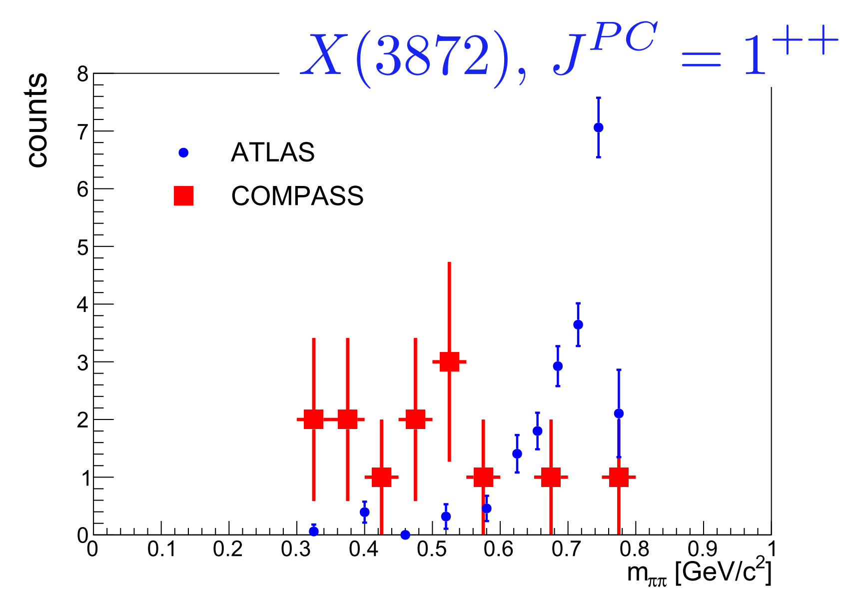
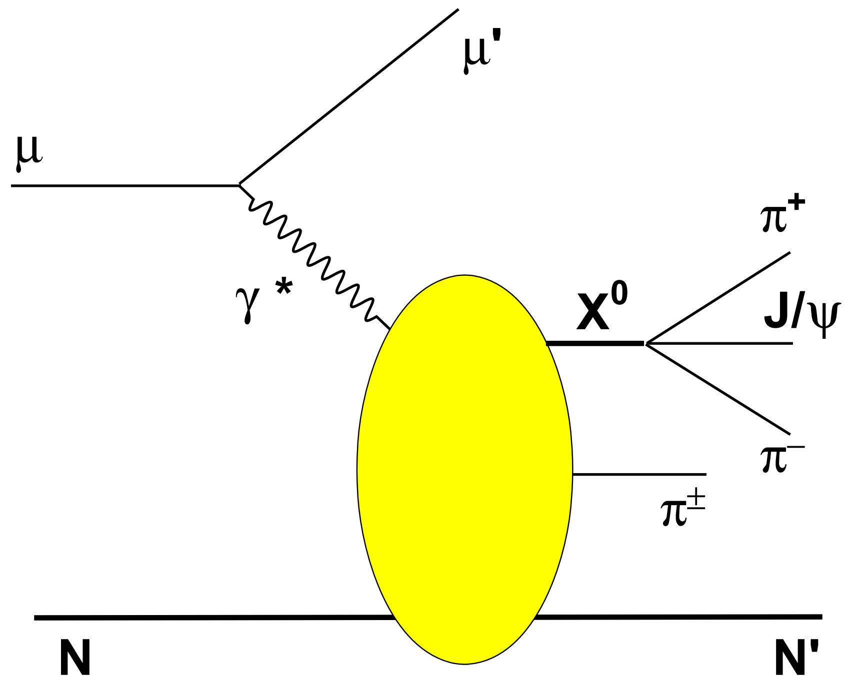




Search for exclusive production of X(3872)

PLB 783 (2018) 334–340



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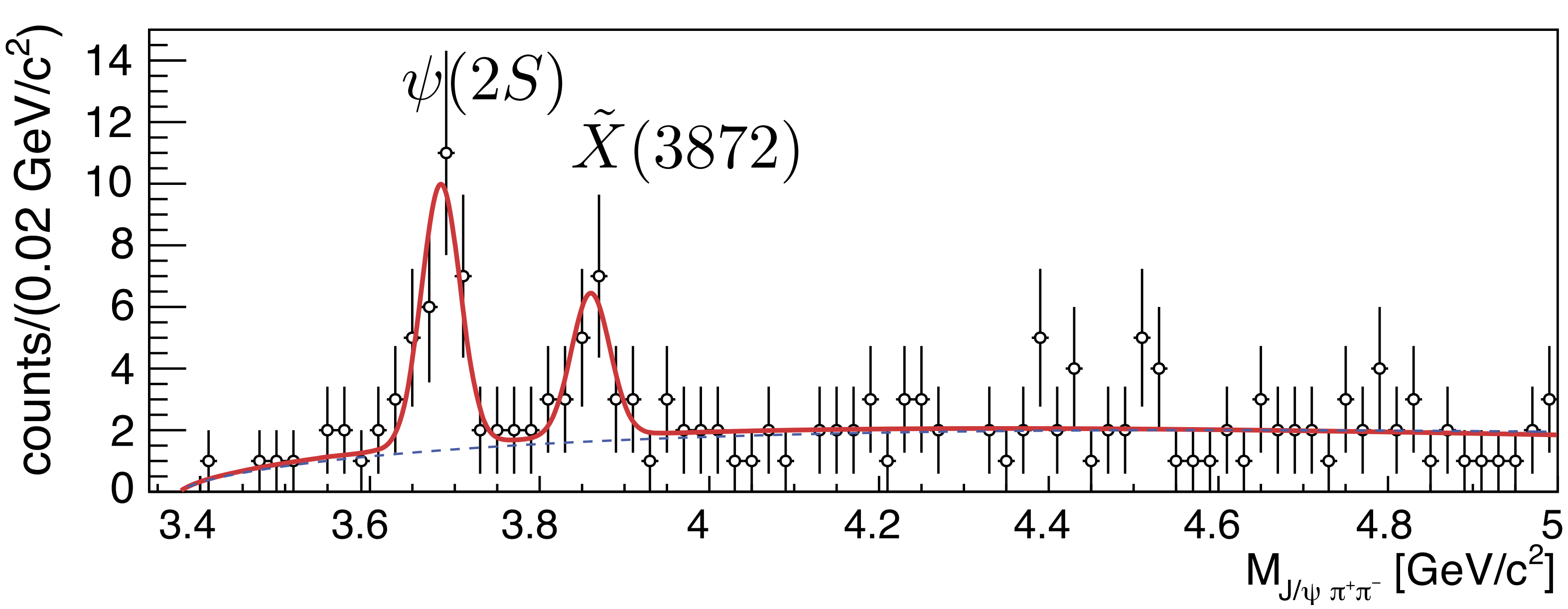

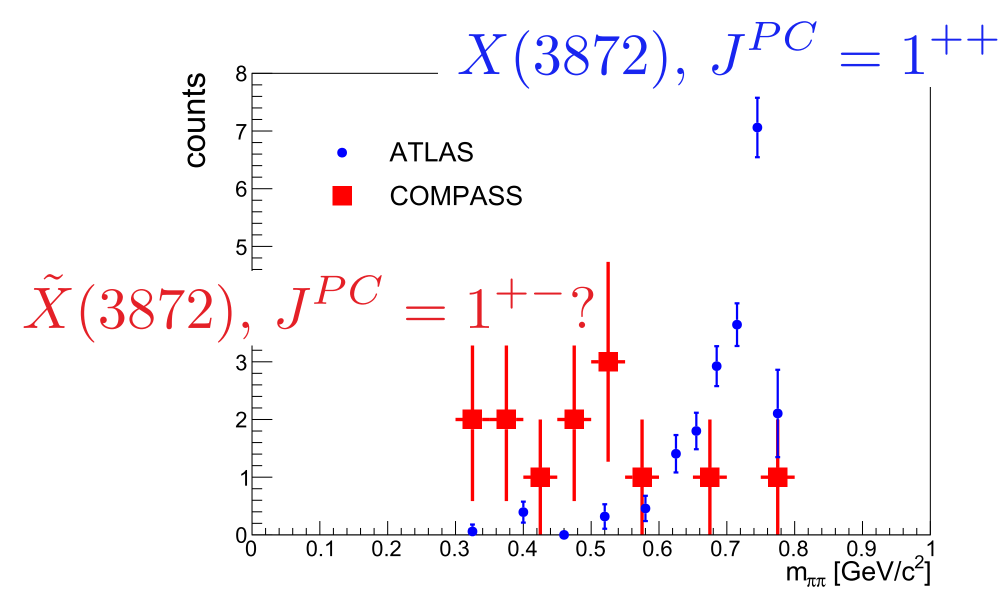

Longitudinal double-spin asymmetries in single-hadron production

$$A_{LL} = \frac{(\sigma^{\leftrightarrows} - \sigma^{\leftleftarrows})}{(\sigma^{\leftrightarrows} + \sigma^{\leftleftarrows})} \longrightarrow \Delta G$$

- hadron $p_T > 1$ GeV
- $Q^2 < 1$ GeV^2

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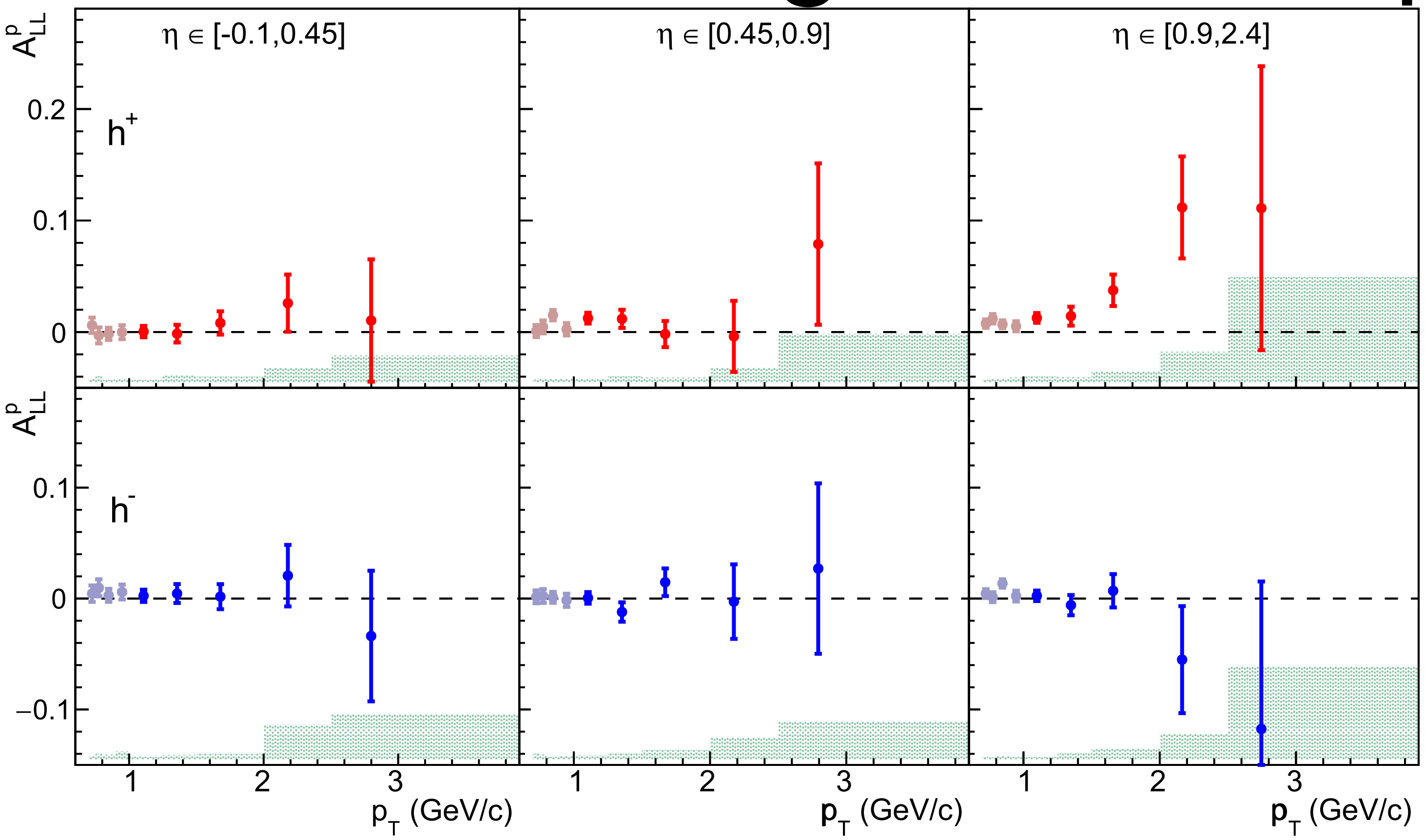
See also: HERMES, JHEP 1008 (2010) 130

Longitudinal double-spin asymmetries in single-hadron production

PLB 753 (2016) 573–579



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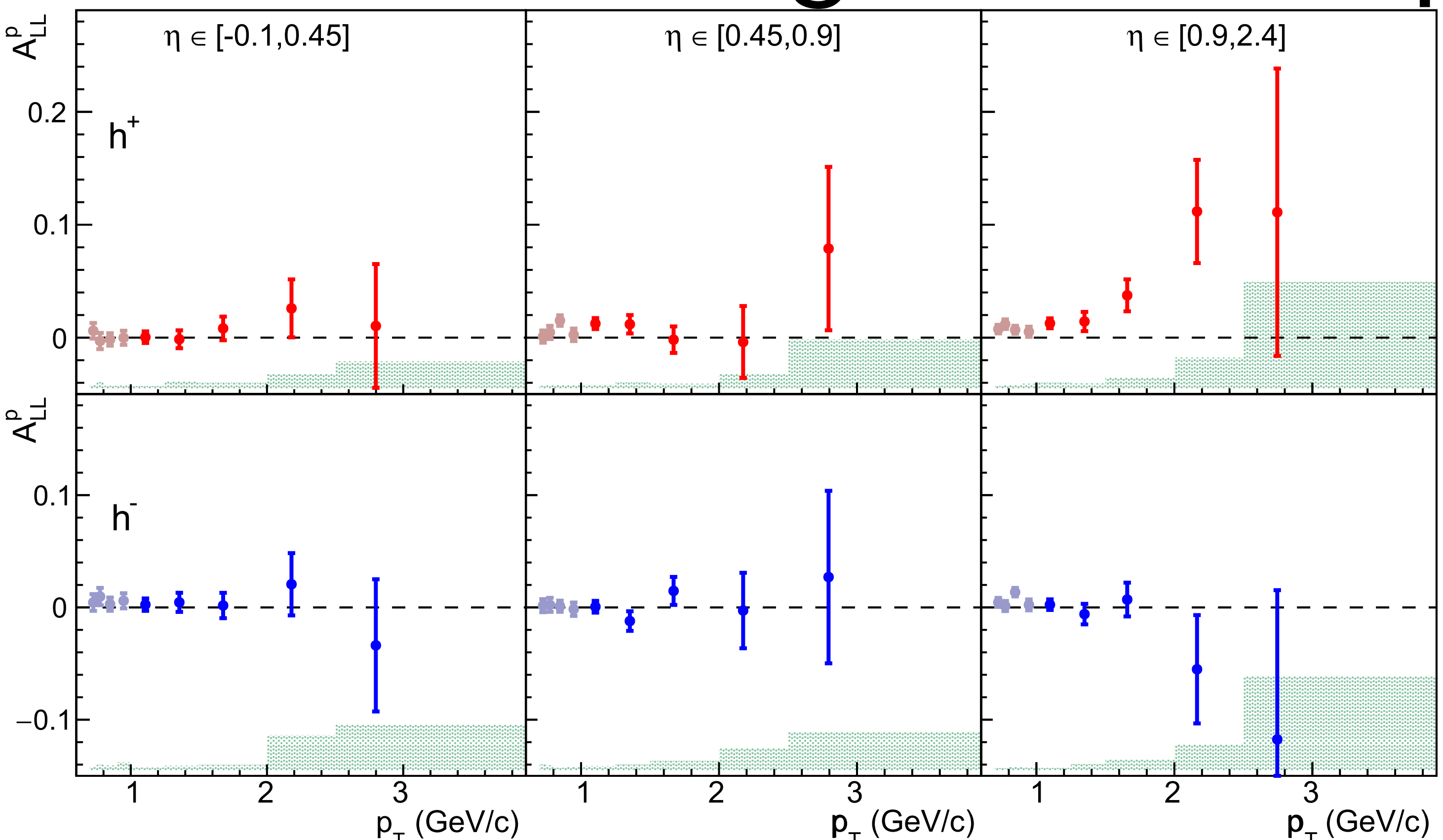
PLB 753 (2016) 573–579



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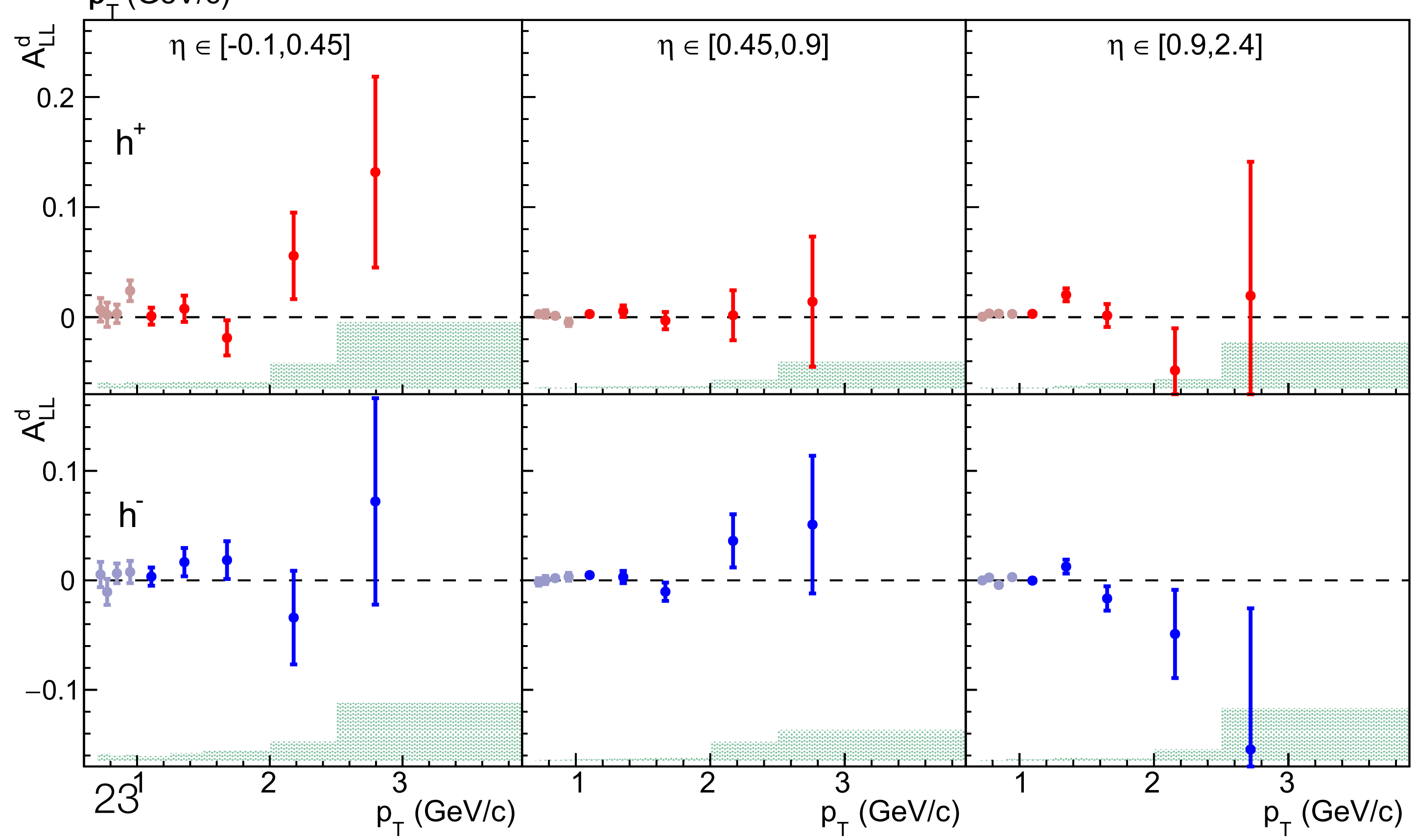
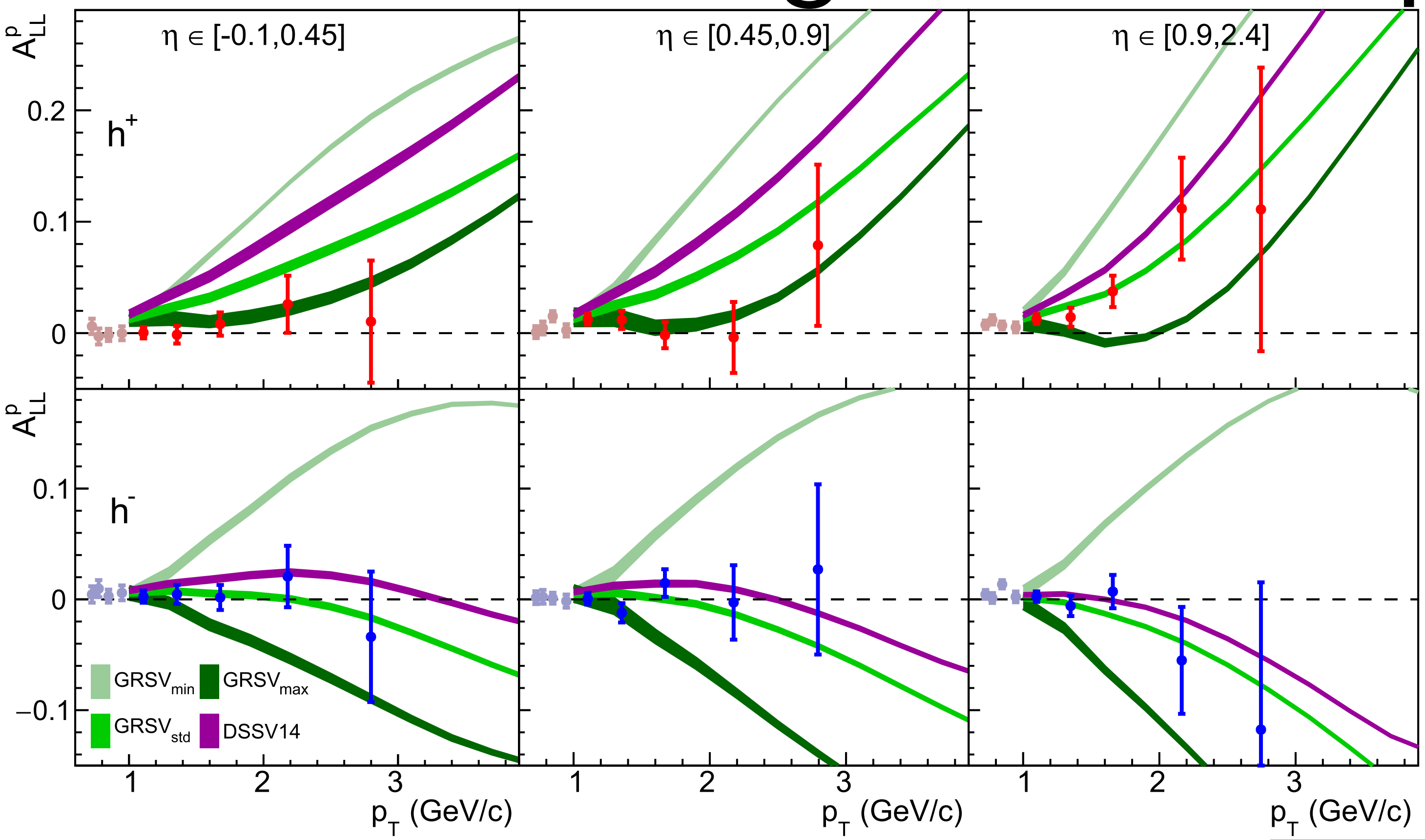


Longitudinal double-spin asymmetries in single-hadron production

PLB 753 (2016) 573–579



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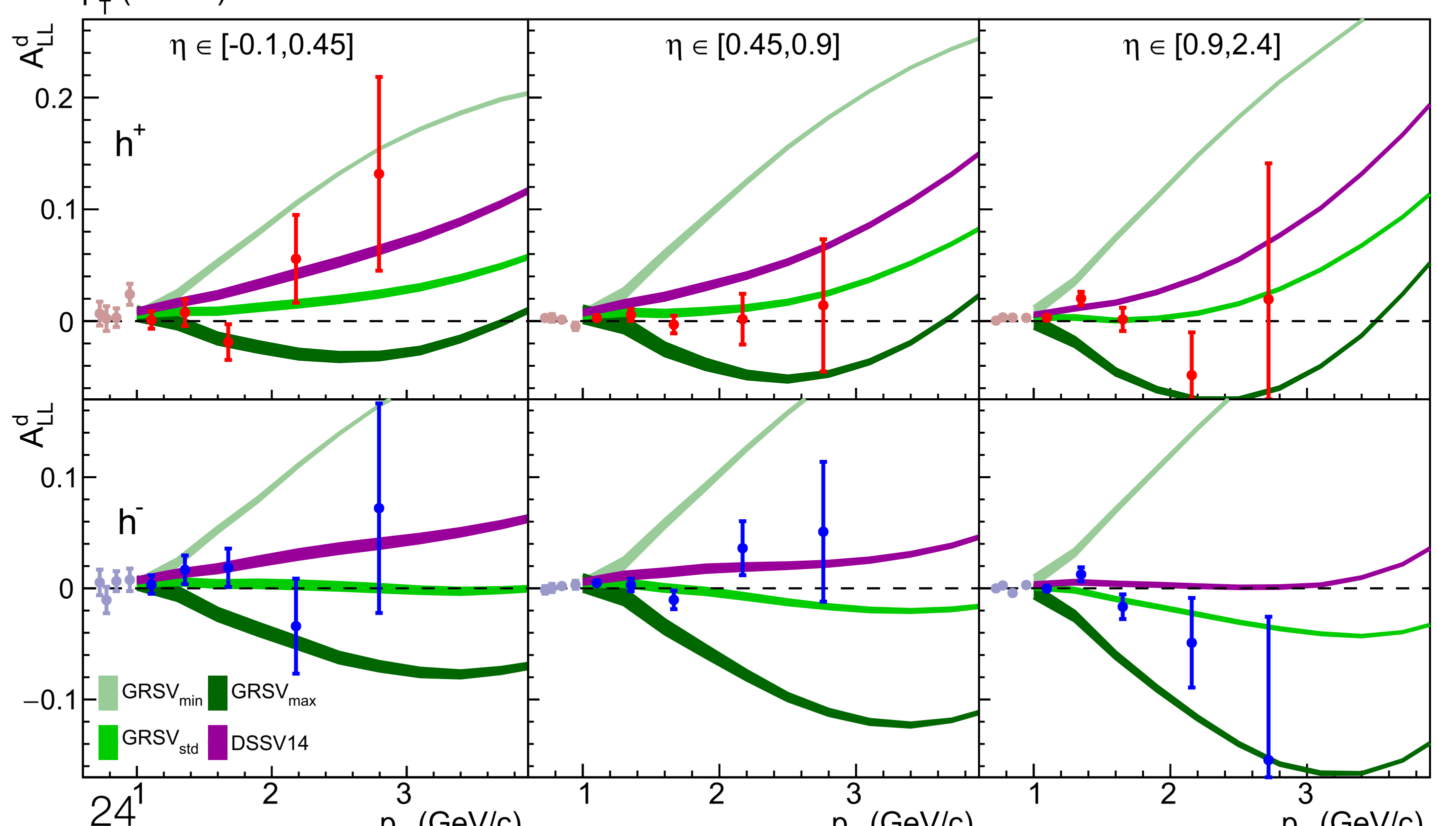


- NLO predictions:
  B. Jäger et al. Eur. Phys. J. C 44 (2005) 533
- photon PDF: GRS
- spin-independent PDF CTEQ6M
- FF: D. de Florian et al. PRD 91 (2015) 014035
- spin-dependent PDFs:
  - $GRSV_{min}$: Δg(x)=-g(x) (ΔG=-0.6)
  - $GRSV_{max}$: Δg(x)=g(x) (ΔG=0.7)
  - $GRSV_{std}$: (ΔG=0.2)
  - $GRSV_{DSSV14}$: (ΔG=0.1)

Summary

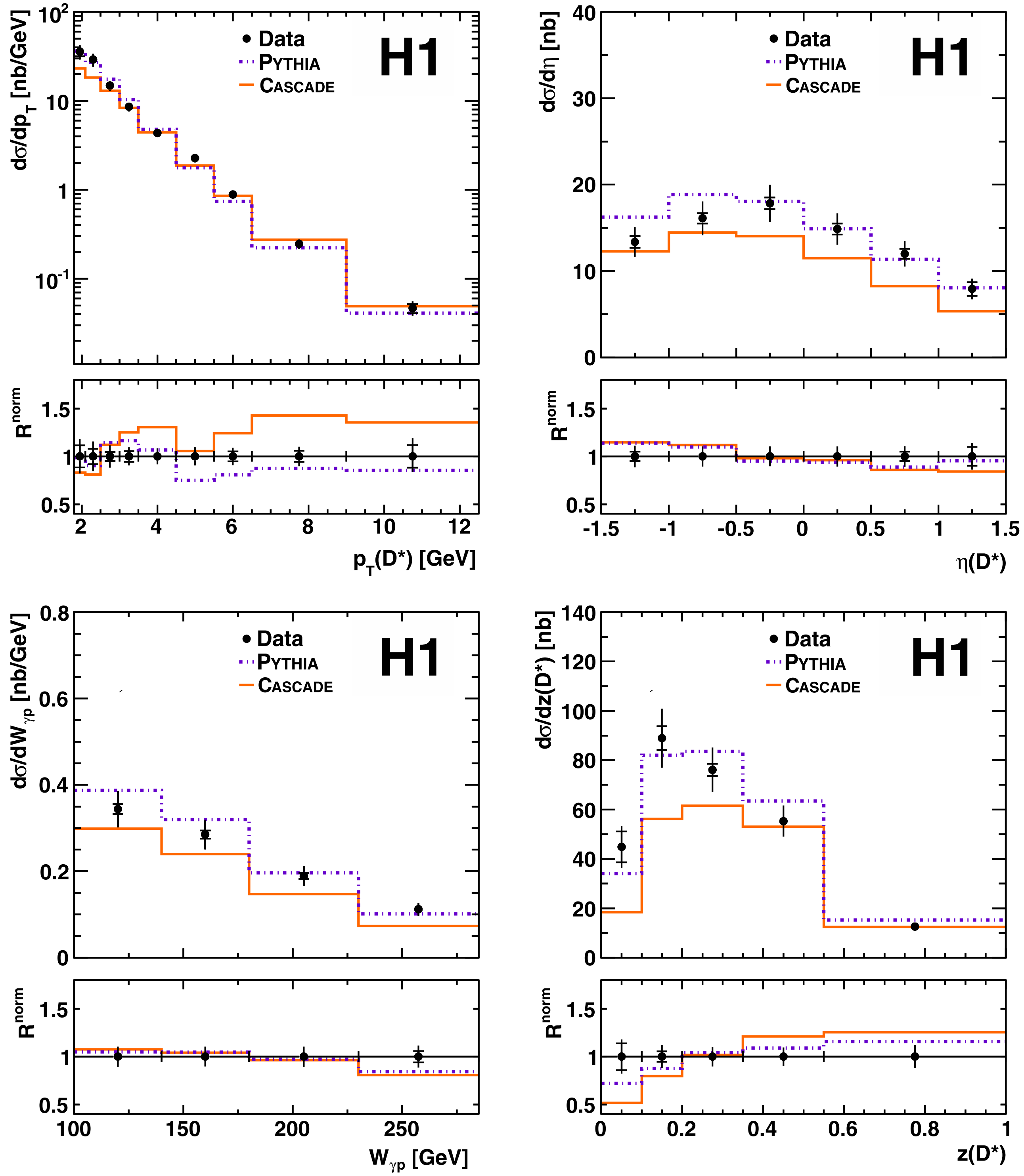
Interesting physics to be done in photoproduction!

- Access to spin-independent PDFs via charm and beauty production
- Access to GPDs via exclusive processes
- Search for new resonance states
- Access to gluon spin-dependent PDF via double-spin asymmetries of high-p_T hadrons

back up

Inclusive D* results

Eur. Phys. J. C 72 (2012) 1995



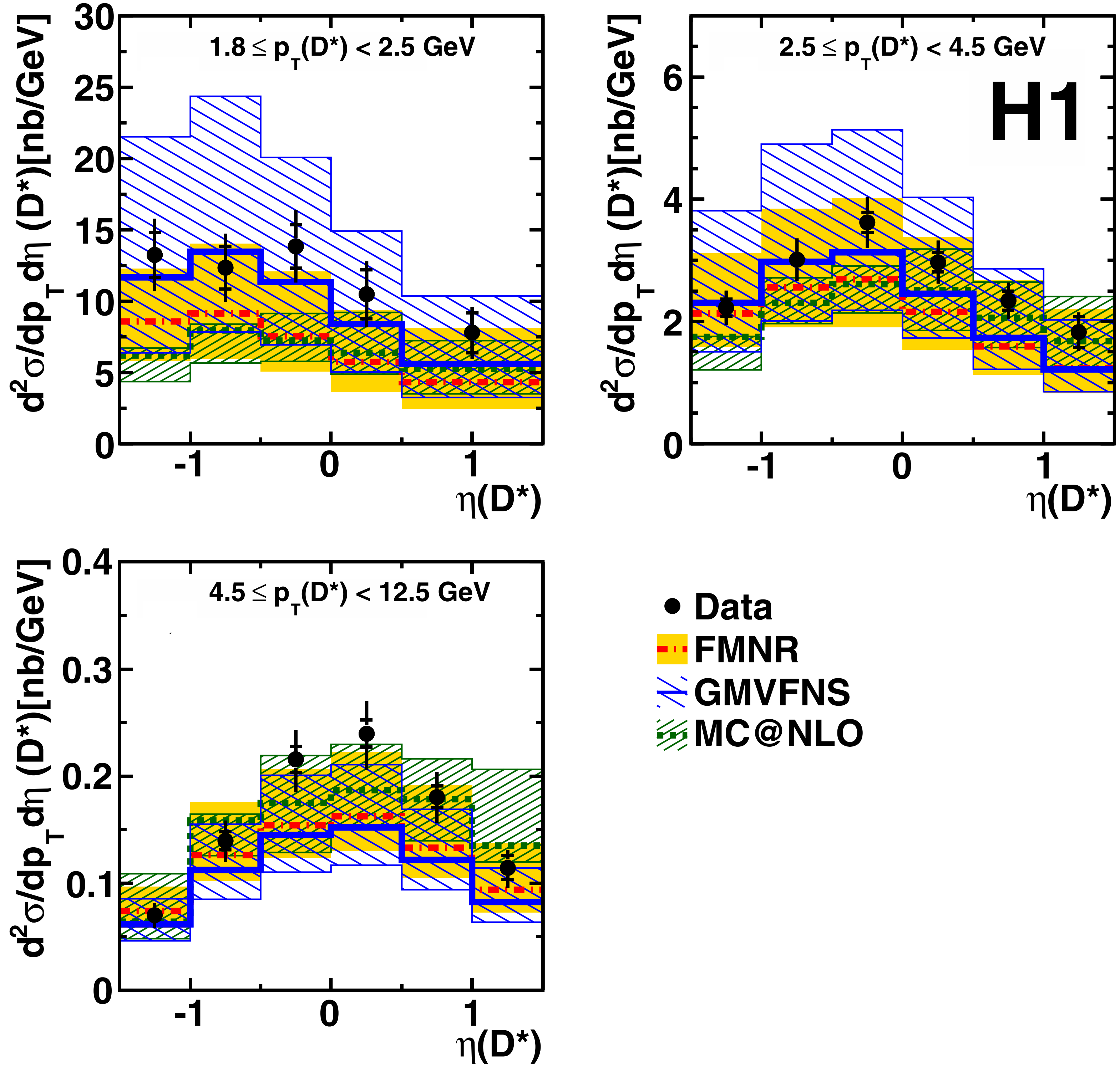
- PYTHIA:
  - LO
  - collinear factorisation
  - direct+resolved
  - m_c=0
  - proton PDF: CTEQ6L
  - photon PDF: GRV-G LO

- CASCADE:
  - LO
  - k_t factorisation
  - direct
  - proton PDF: A0

Inclusive D* results

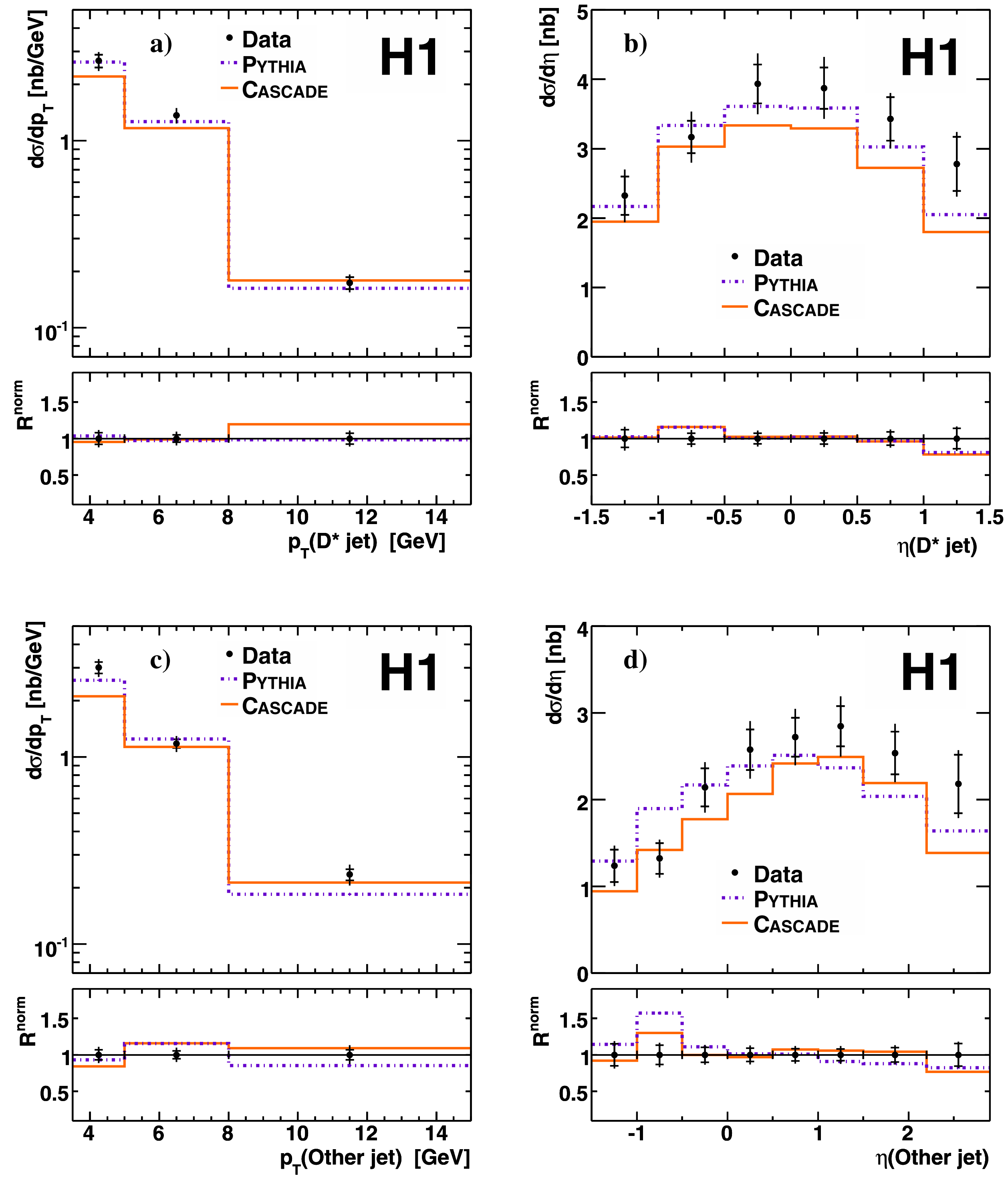
double differential

Eur. Phys. J. C 72 (2012) 1995



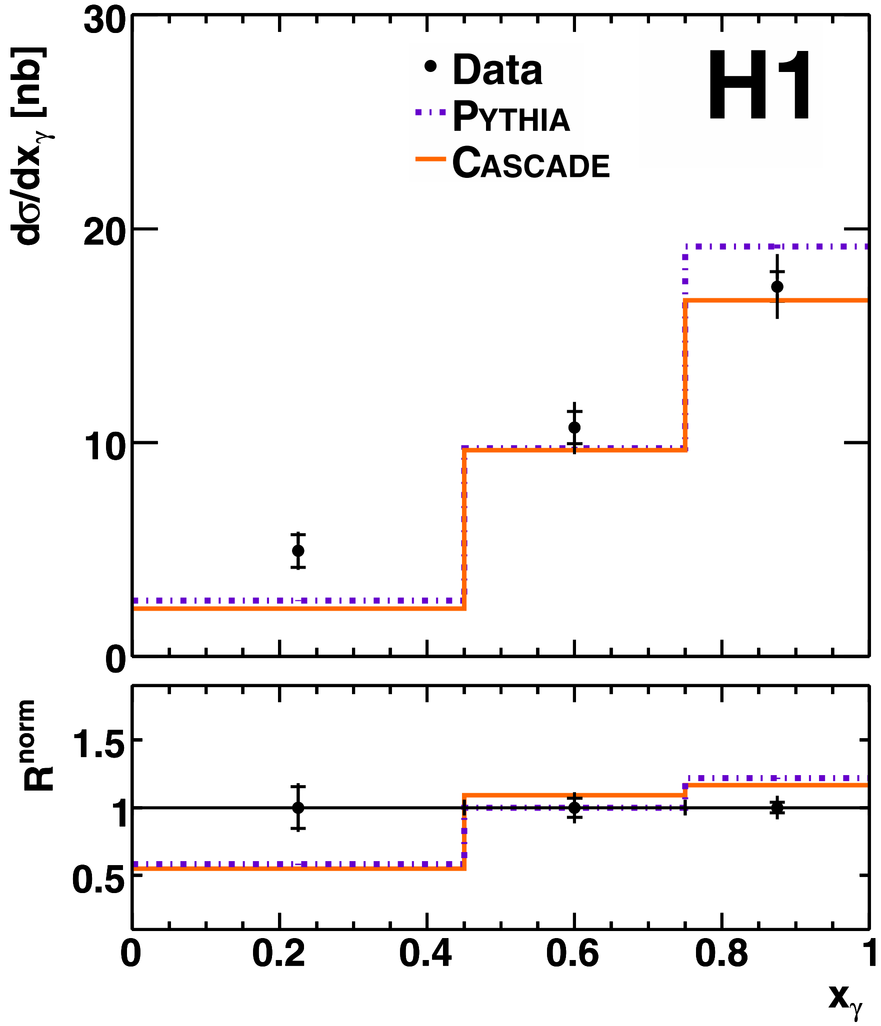
D* tagged dijet results

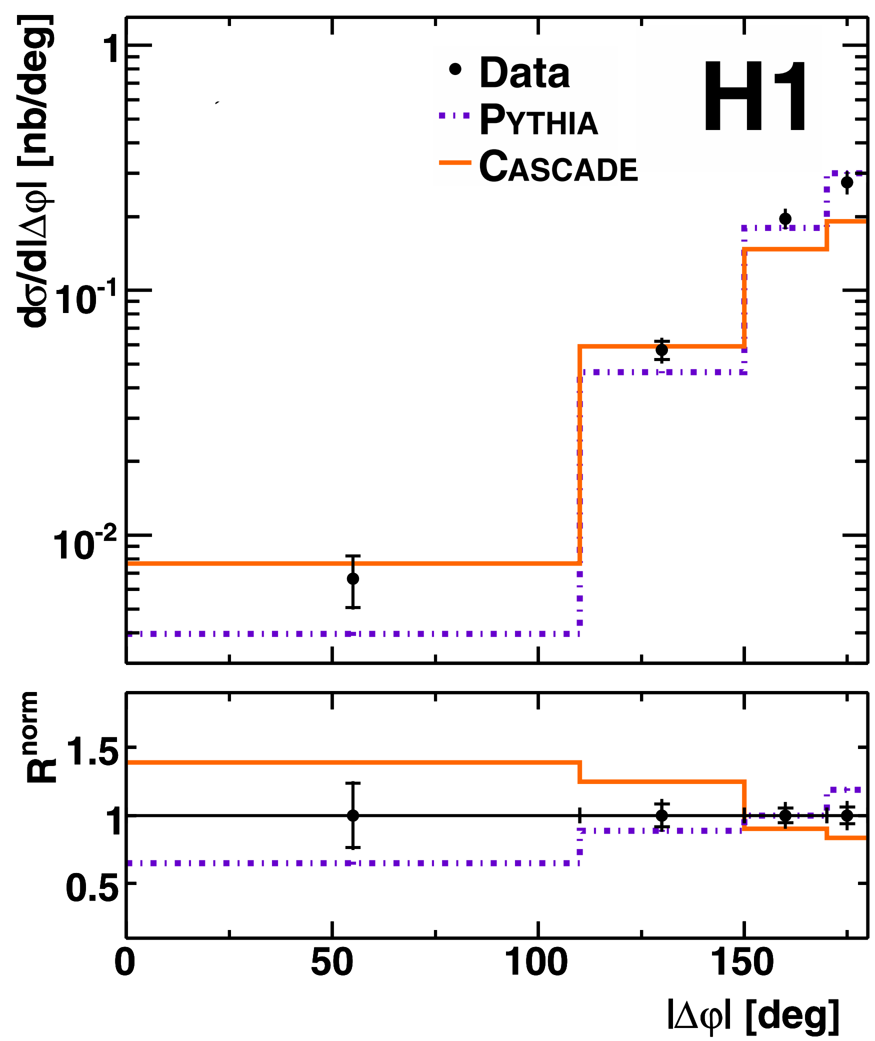
Eur. Phys. J. C 72 (2012) 1995



D* tagged dijet correlations

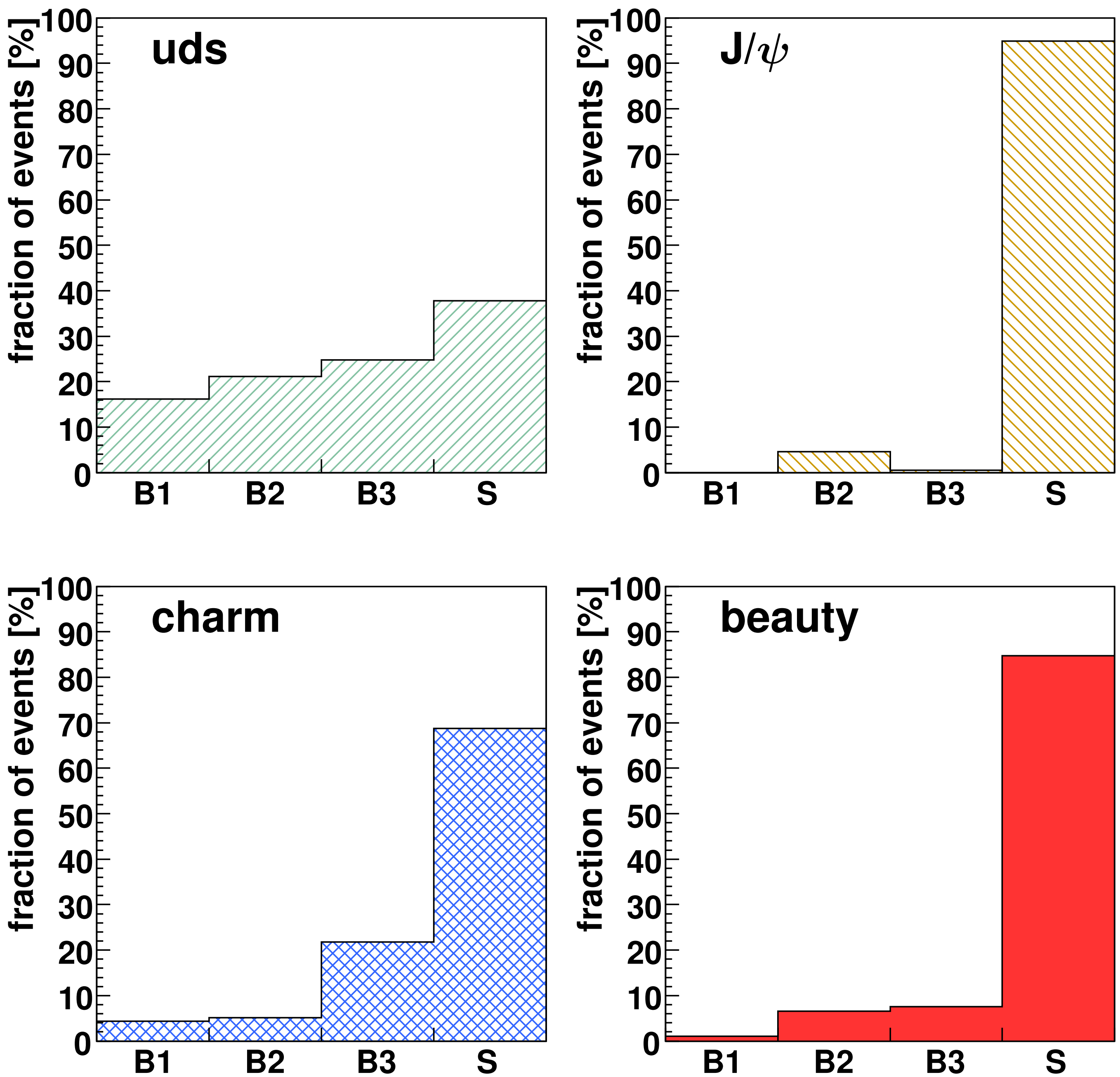
Eur. Phys. J. C 72 (2012) 1995



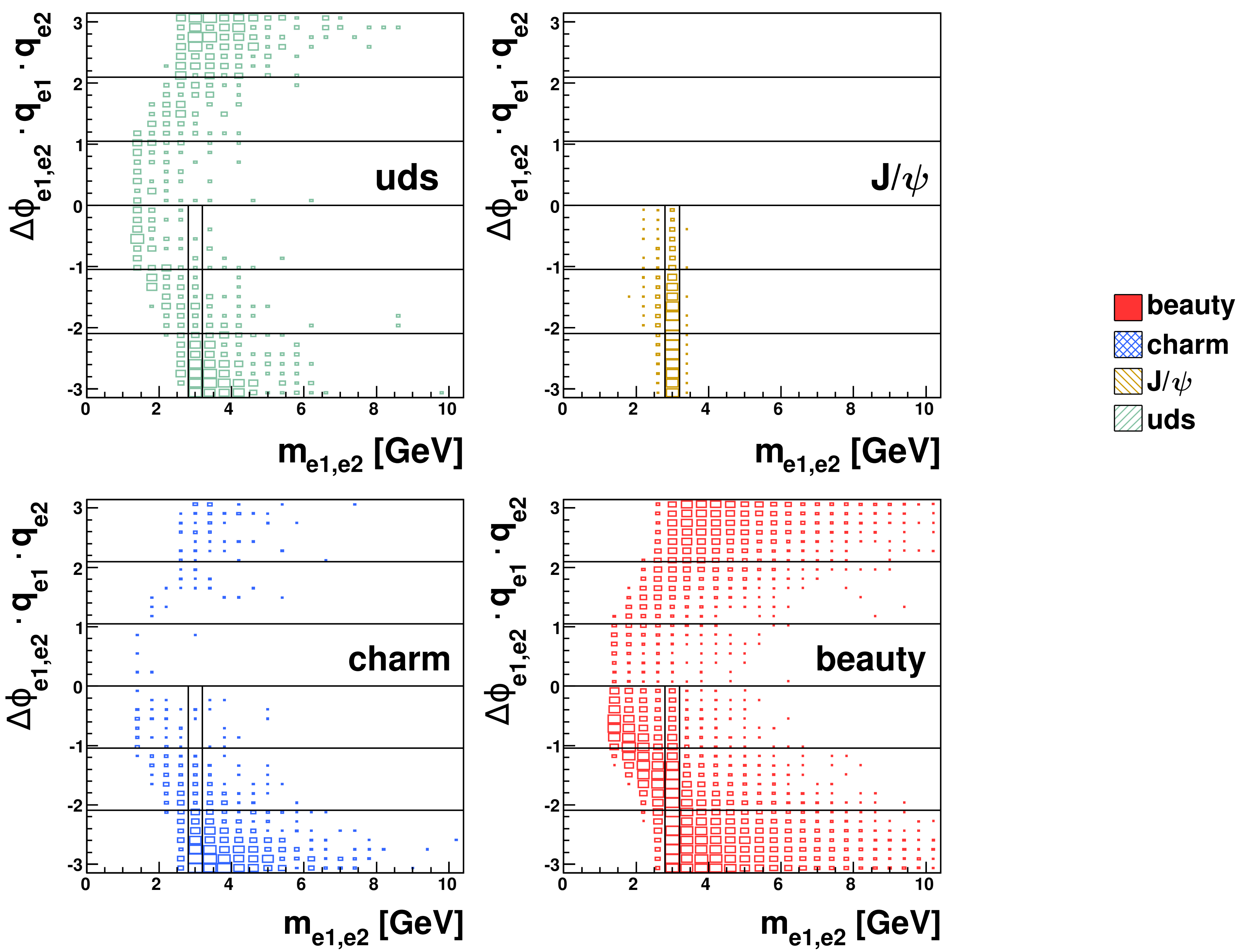


Beauty near threshold: uds background

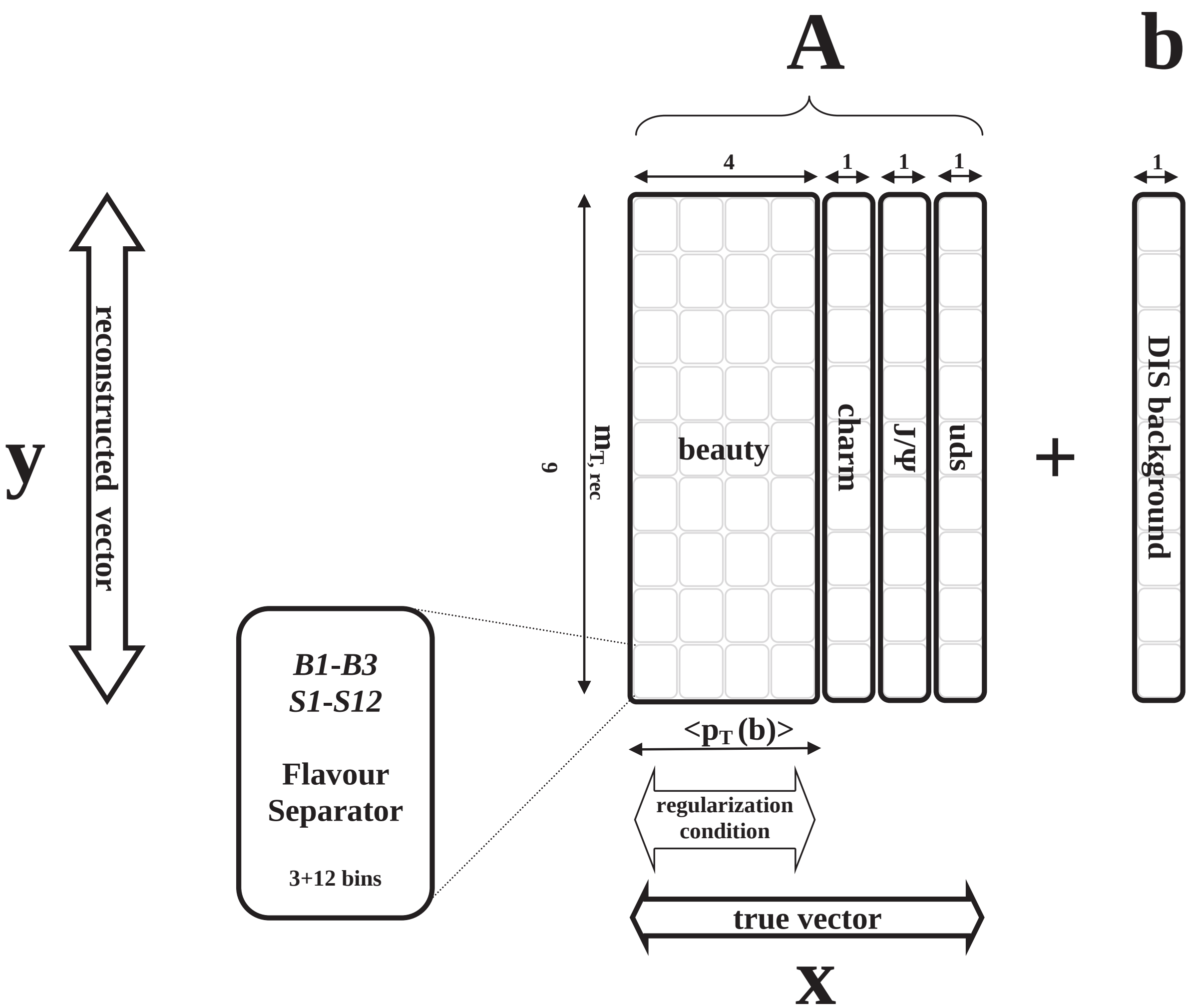
$R^{\max(e1,e2)}_{\mathrm{E,cone}}$	$D^{\min(e1,e2)}_{\mathrm{ele}}$	
	$0.825-0.875$	$0.875-1.0$
$150-350\%$	$B1$	$B3$
$0-150\%$	$B2$	S

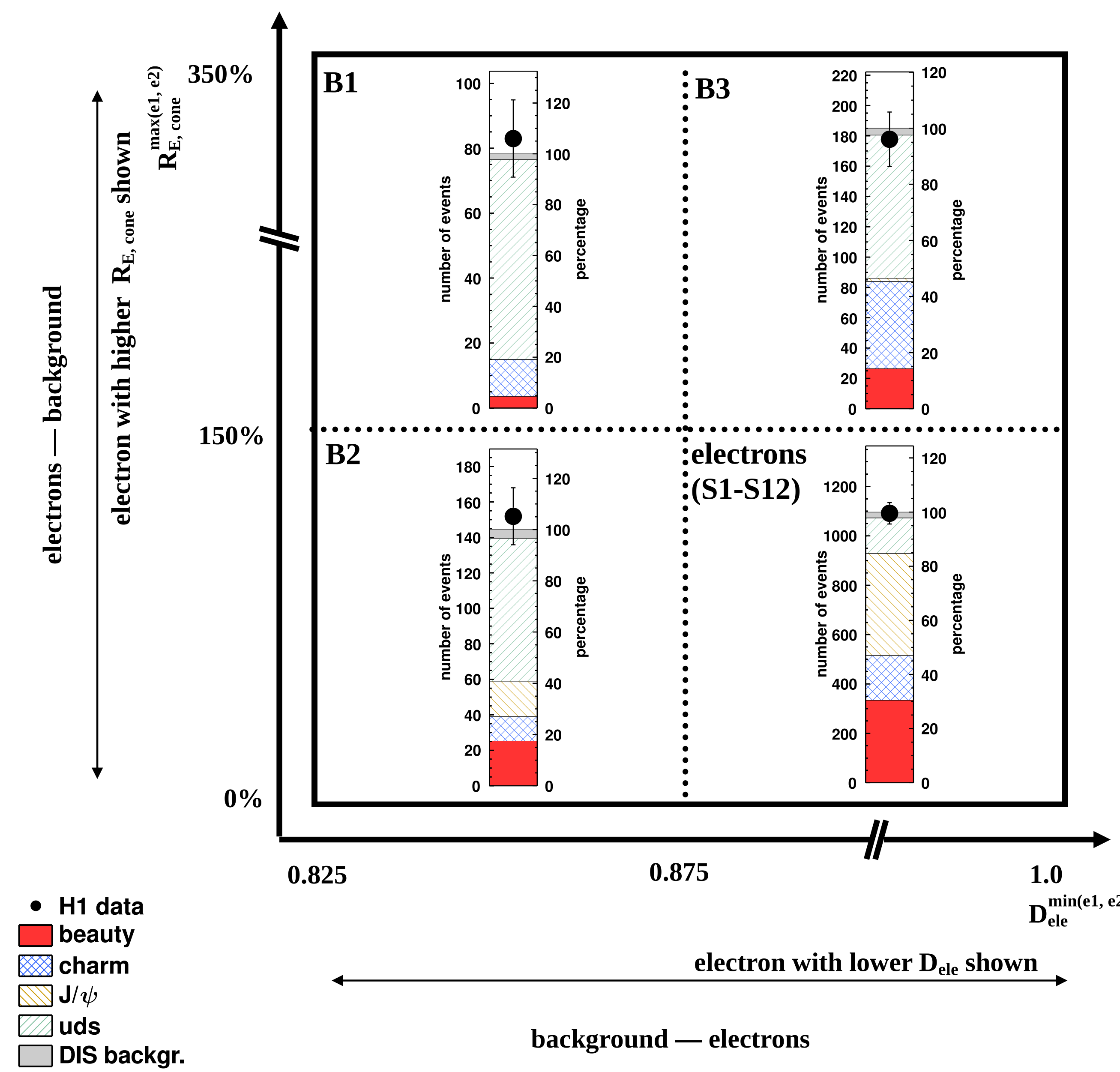


Beauty near threshold: background

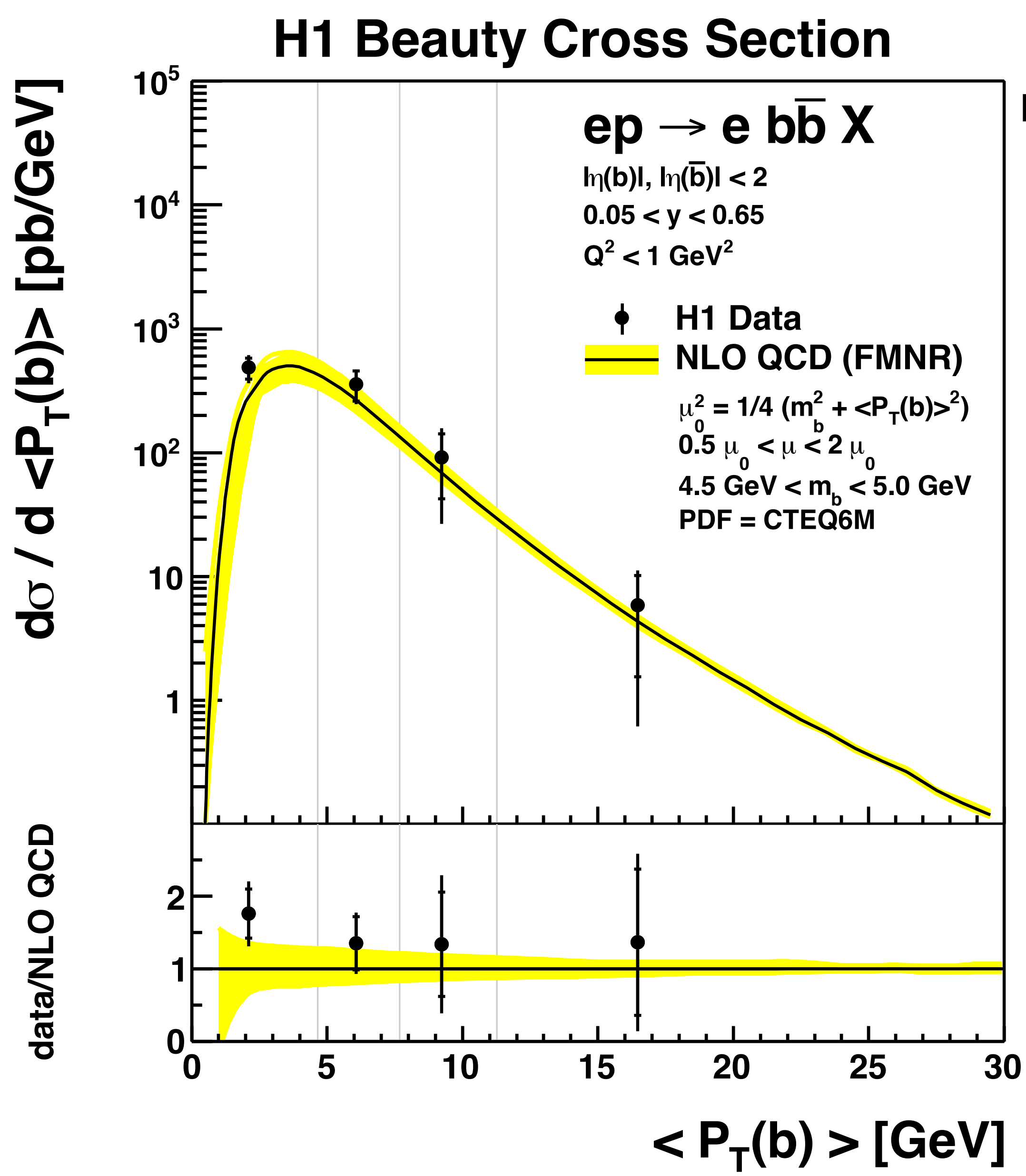


Beauty near threshold: unfolding and fitting





Beauty near-threshold results



Eur. Phys. J. C 72 (2012) 2148

- FMNR
  - NLO
  - massive scheme
  - proton PDF: CTEQ6M
  - photon PDF: GRV-G HO