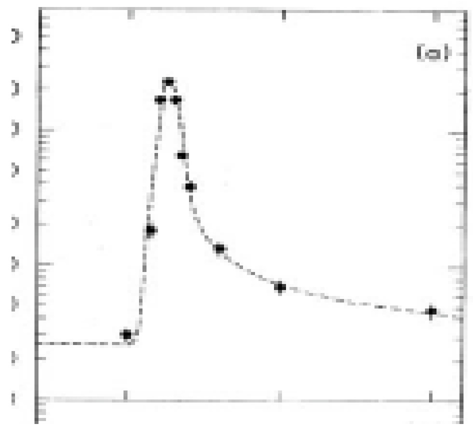
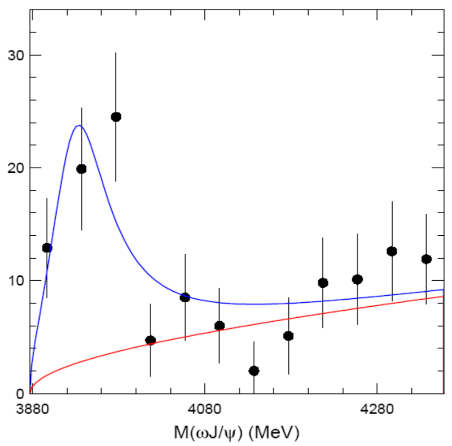
# Heavy Quark Production



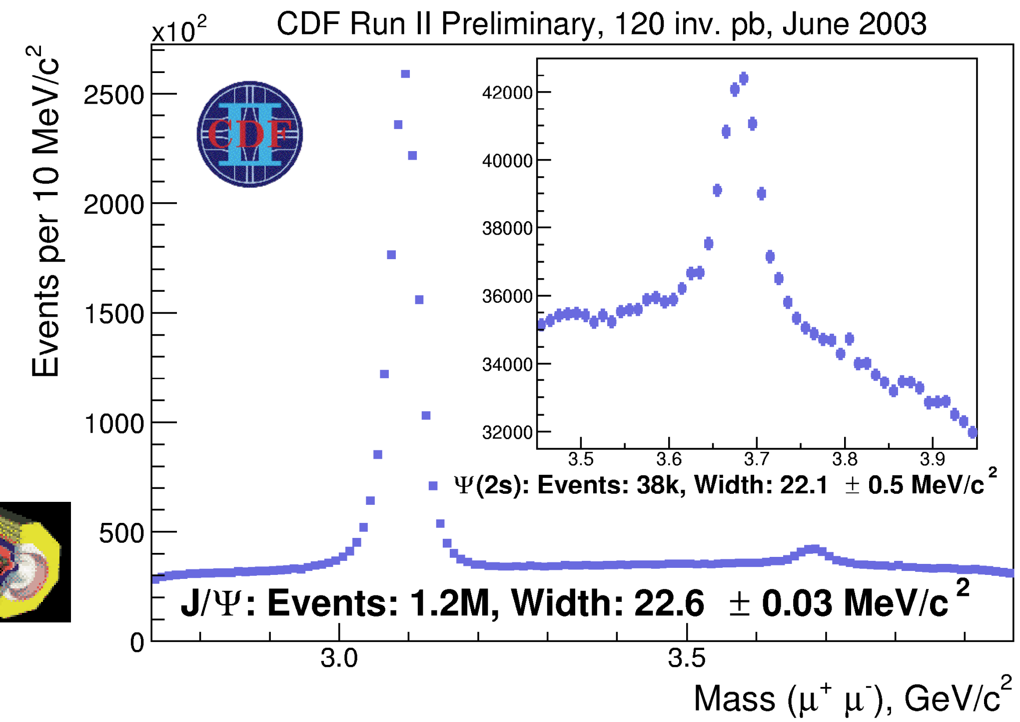

Andreas B. Meyer
DESY

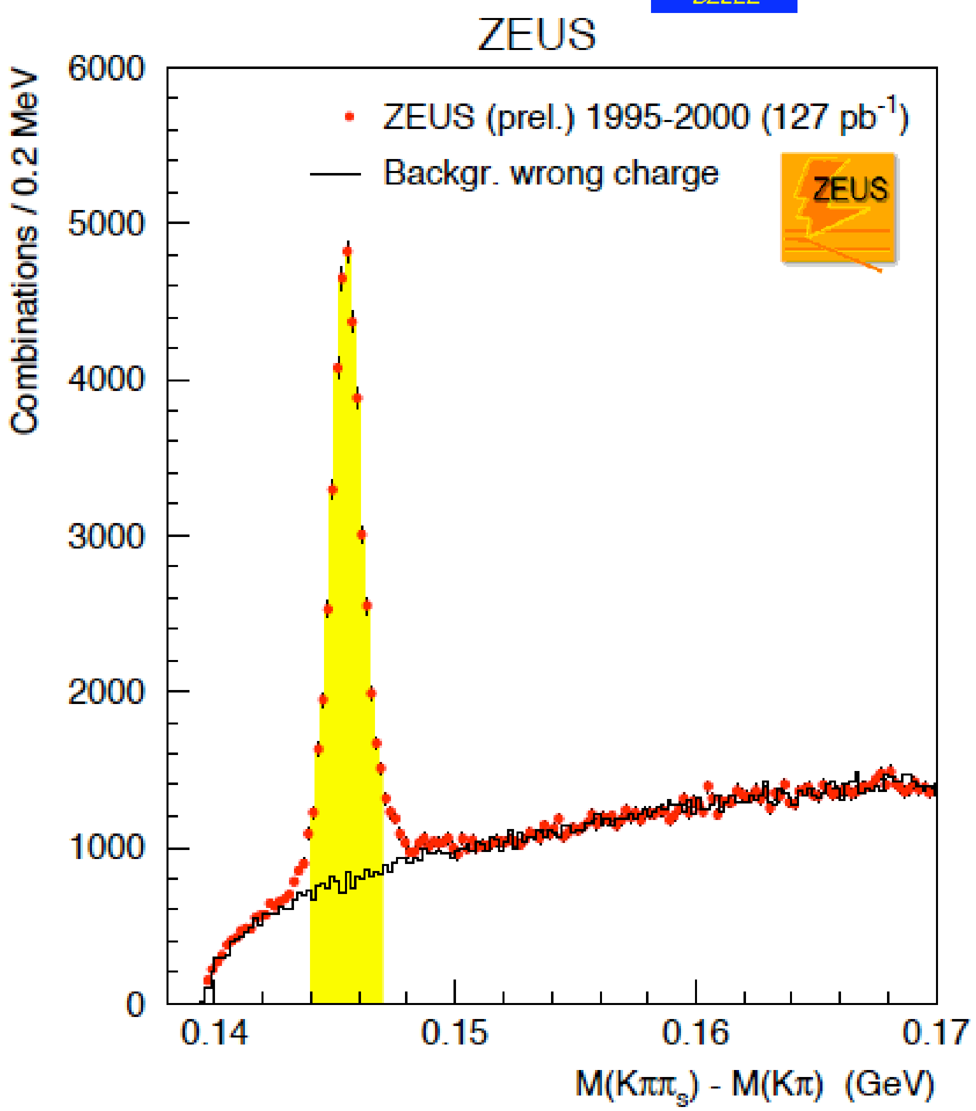


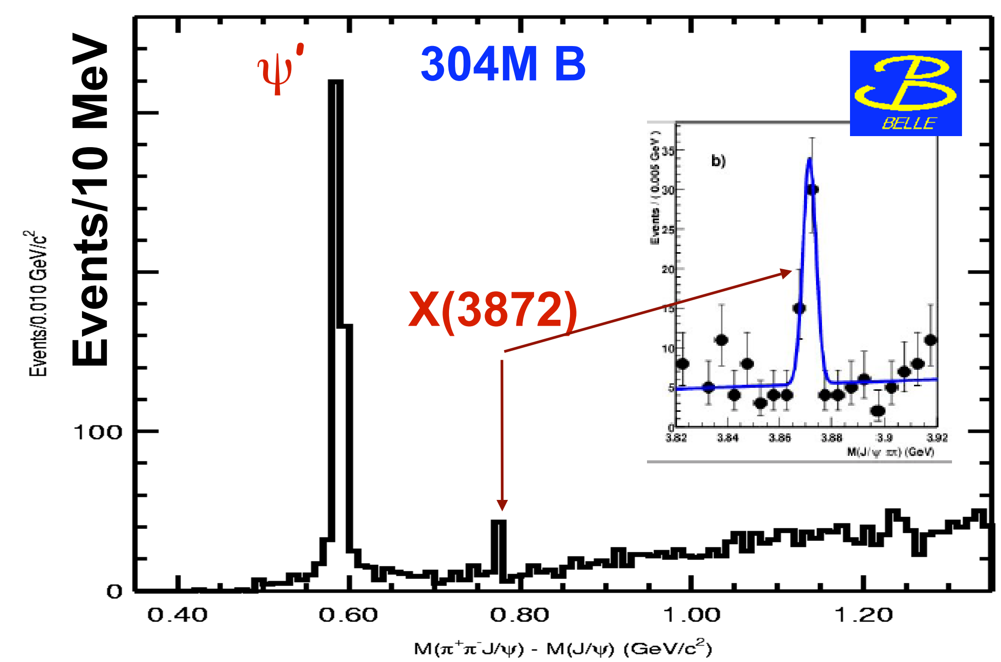

Introduction
Experiments
Recent Results
Photon Structure
Quarkonia

# Experiments

- Initial states:
  - ee, eγ, γγ
  - ep, γp
  - $p\bar{p}$
  - Resonances




Final states:

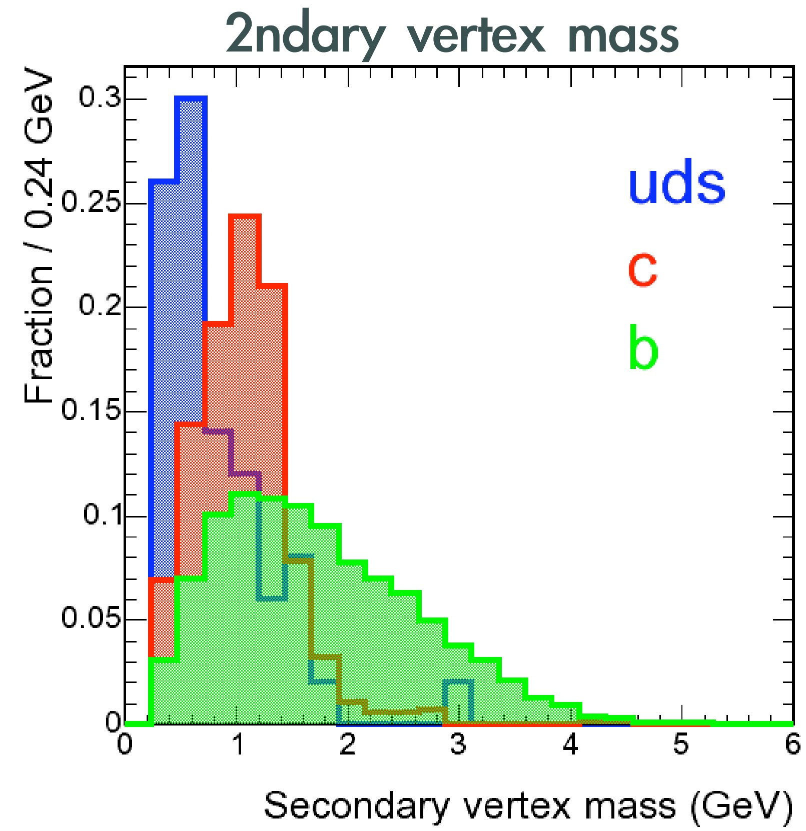
Large samples of charm and beauty events

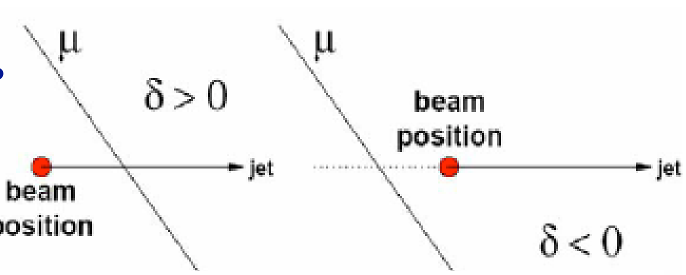
open and quarkonia

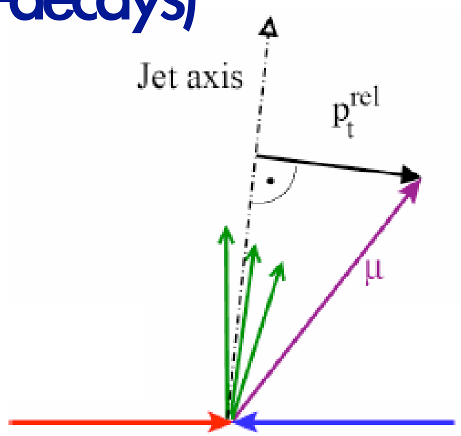
# Heavy Quark Identification

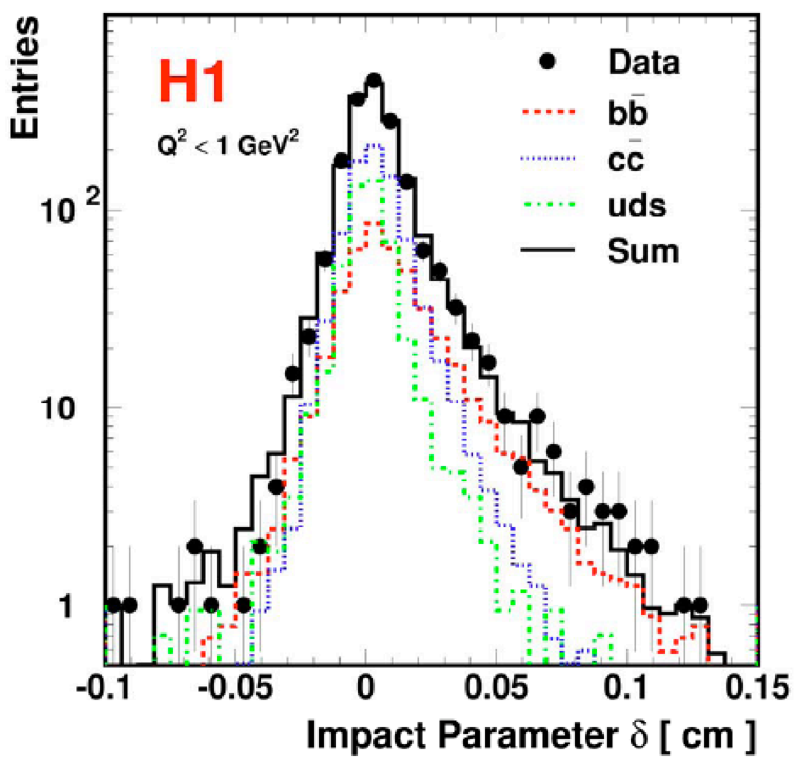
## Distinguish charm and beauty from uds events (→trigger!)

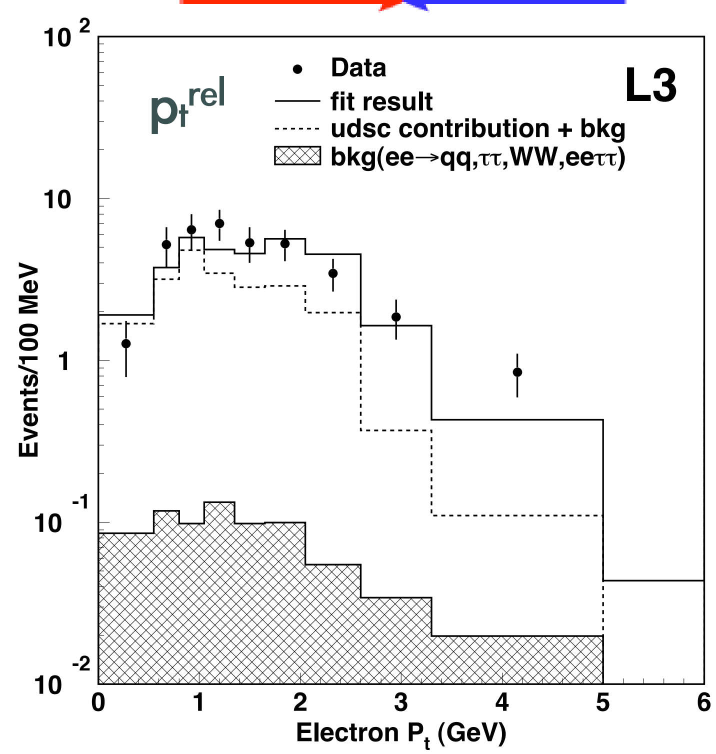
- Full (or partial) resonance reconstruction (previous slide)
- Lifetime tag (displaced vertices, impact parameter)
- Mass tag ($p_t^{rel}$, jet- or vertex mass)
- Lepton tag (leading particles from hq-decays)
- Two-quark correlations
- ...

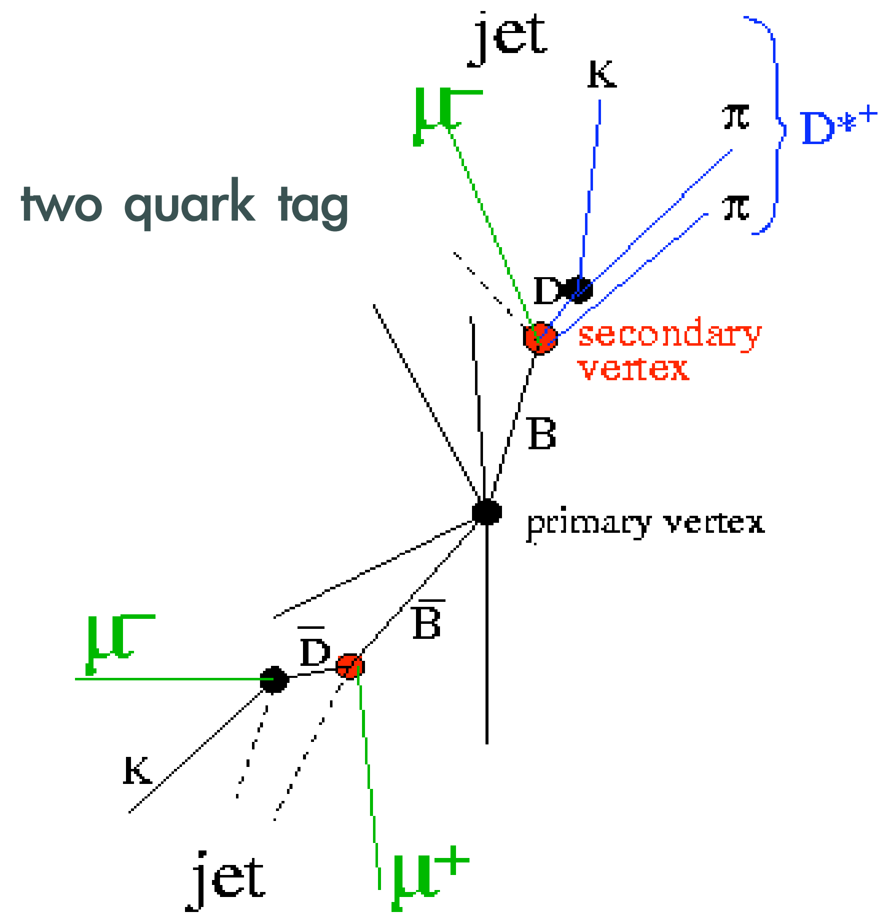


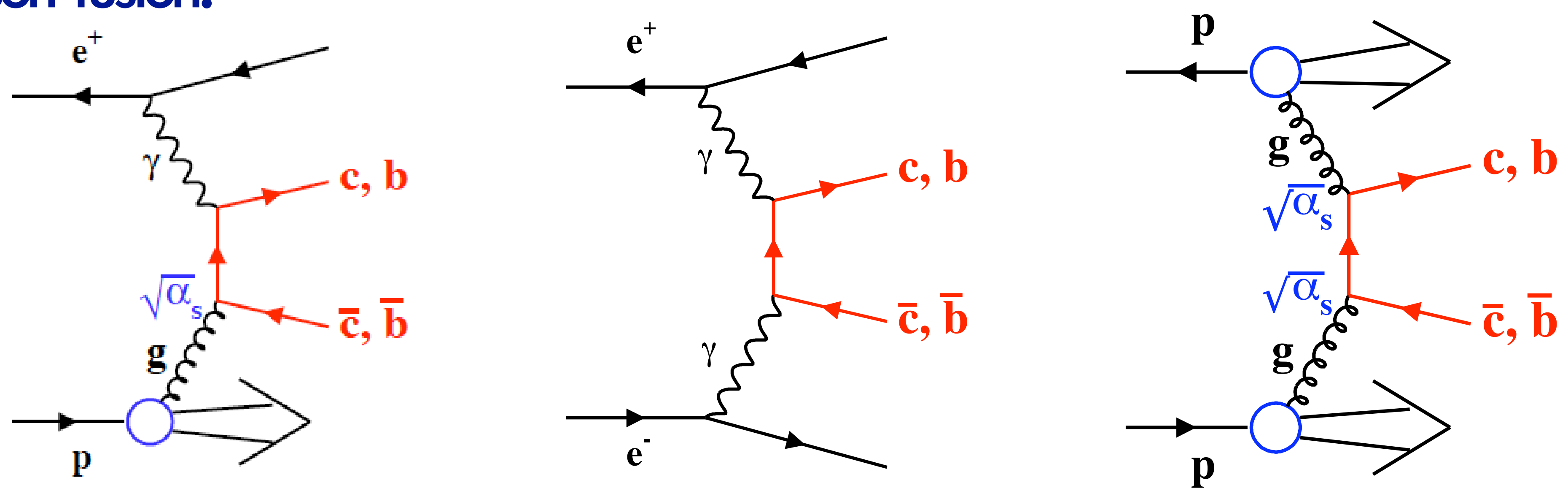




cf. e.g. P.Thompson, C.Grab

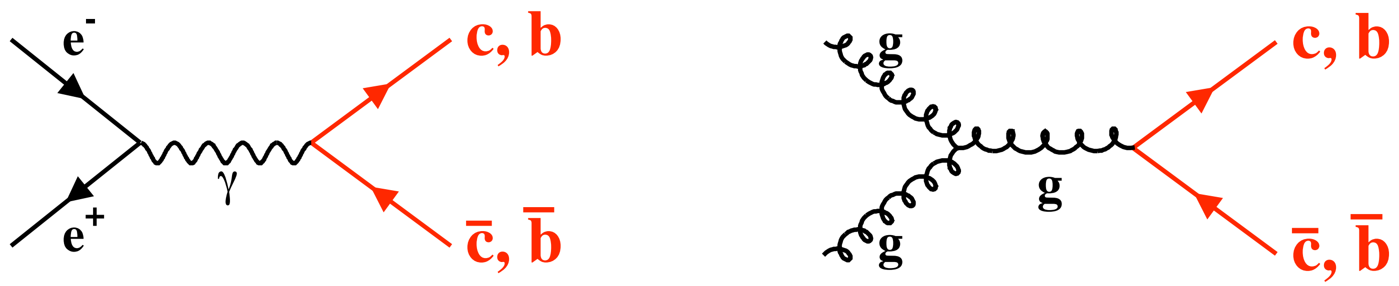
# HQ Production Processes (LO)

Boson-boson fusion:

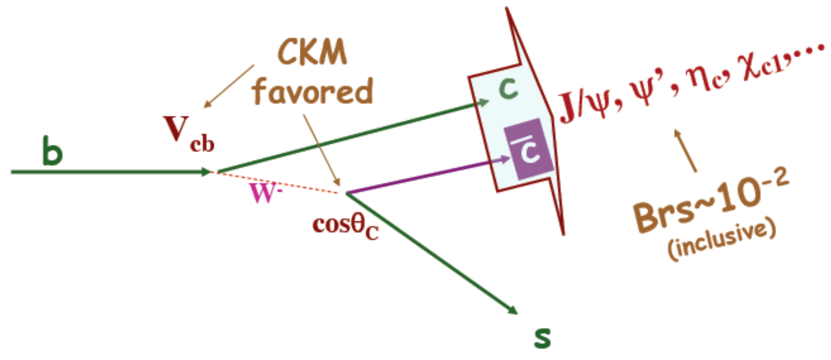



HERA, LEP: additional important contributions due to hadronic structure of the photon

Flavour creation from virtual boson ($\gamma$, $Z^0$, g)

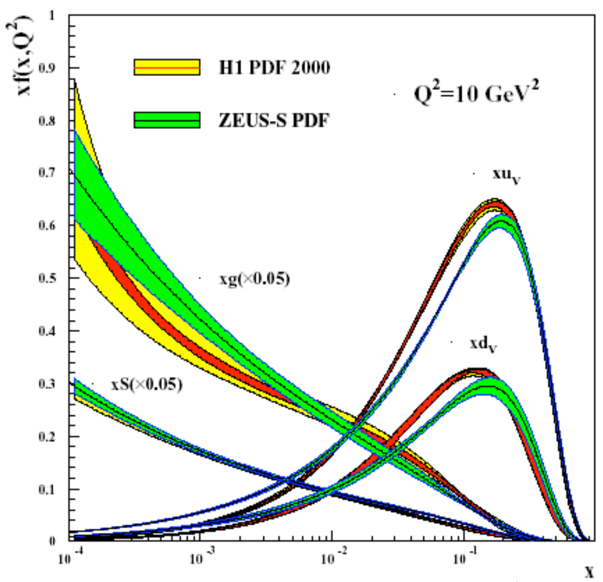



Also: charm from B-decays

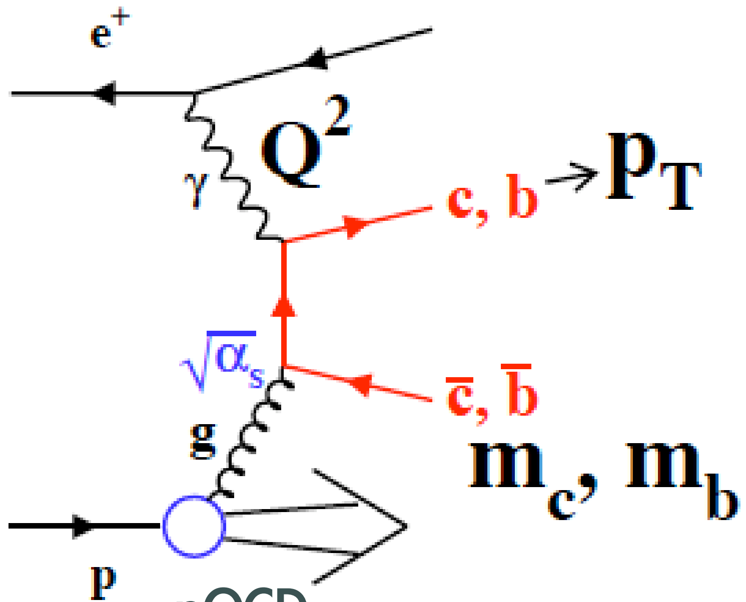


# QCD Predictions

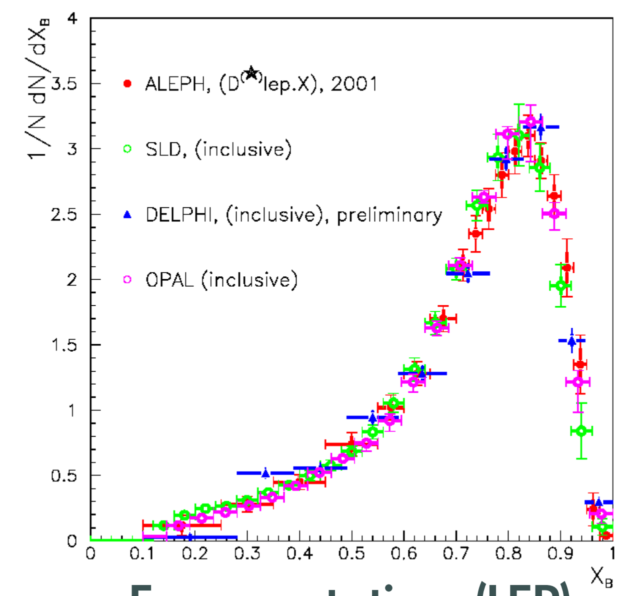
## Factorization: Proton and/or Photon Structure ⊗ Perturbative QCD ⊗ Fragmentation




p-Structure Functions (HERA)

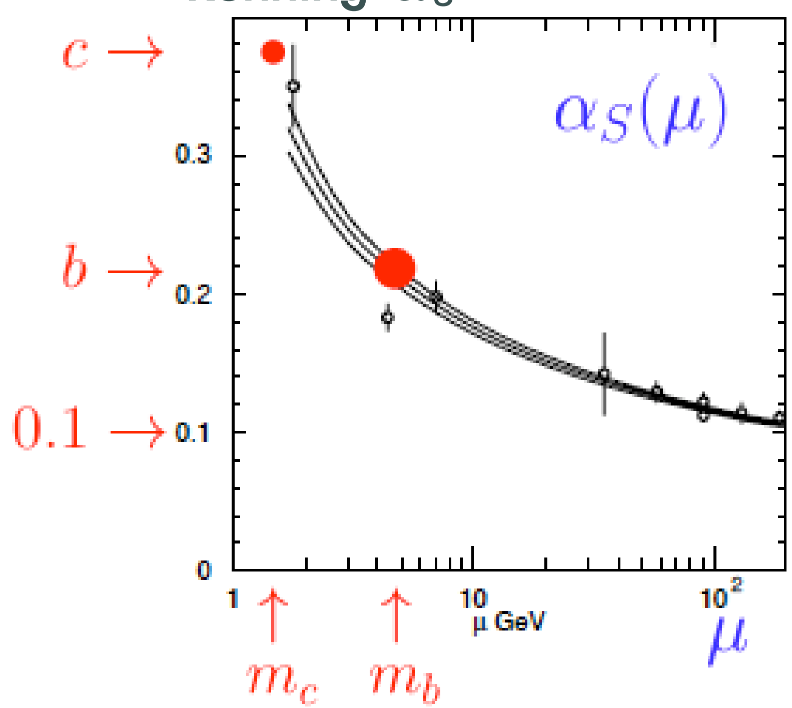



pQCD




Fragmentation (LEP)

Running $\alpha_s$




**Perturbative QCD:**

Heavy quark mass provides a hard scale $m_{c,b}^2$

Other scales: $Q^2, p_t^2$ ⟶ multiscale problem

Interplay between the different scales ?

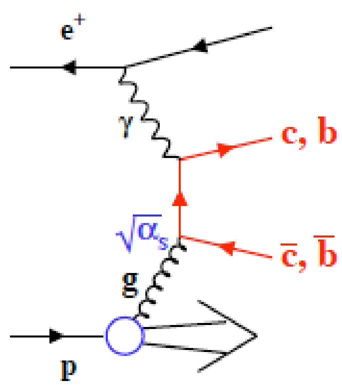
Non-perturbative components (input pdfs, fragmentation):
Assume (and possibly test) universality

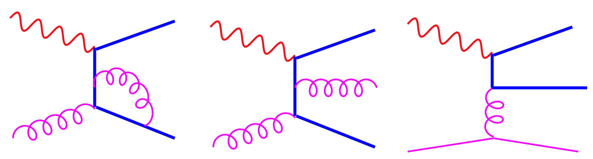
Consistent picture between ee, ep, $\gamma$p, $\gamma\gamma$, p$\bar{\text{p}}$ ?
Want/need predictive power for new phenomena (e.g. LHC)

# Calculations

Different approximations to avoid large terms $[\alpha_s \ln(\mu^2/m_c^2)]^n$ with $\mu^2 = Q^2$ or $p_t^2$

**massive scheme:**
c,b: dynamically produced

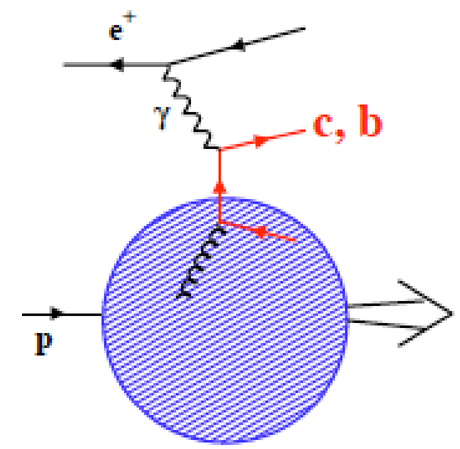


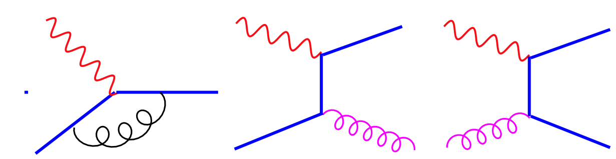



leading NLO graphs

neglect $[\alpha_s \ln(\mu^2/m_c^2)]^n$
valid at $\mu^2 \approx m_c^2$

**massless scheme:**
c,b: partons in proton or photon



leading NLO graphs

resum $[\alpha_s \ln(\mu^2/m_c^2)]^n$
valid at $\mu^2 \gg m_c^2$

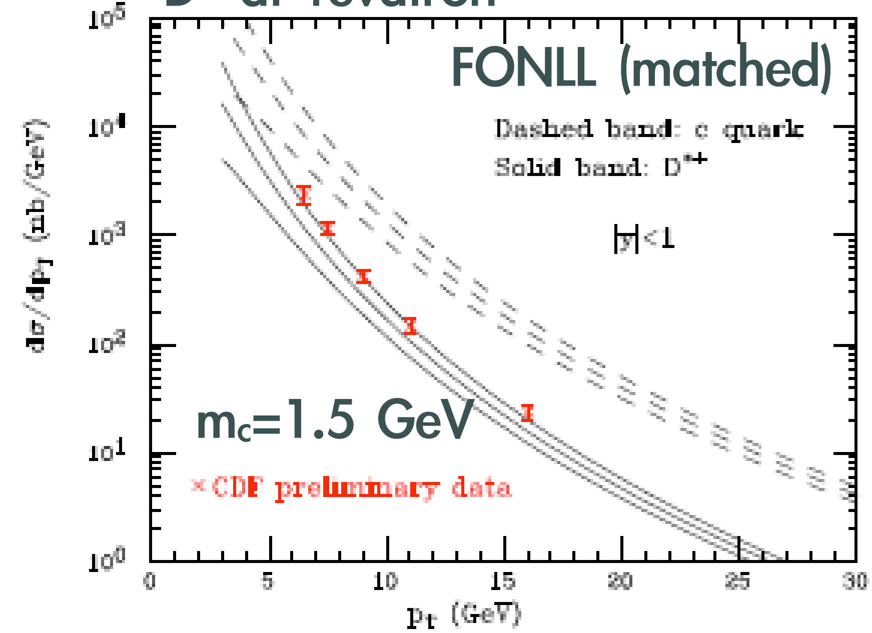
**Variable FNS** (e.g. MRST04, CTEQ6HQ, FONLL):
Interpolate / match between massive and massless

Programs: NLO parton level or LO+PS hadron-level MC (DGLAP or CCFM)

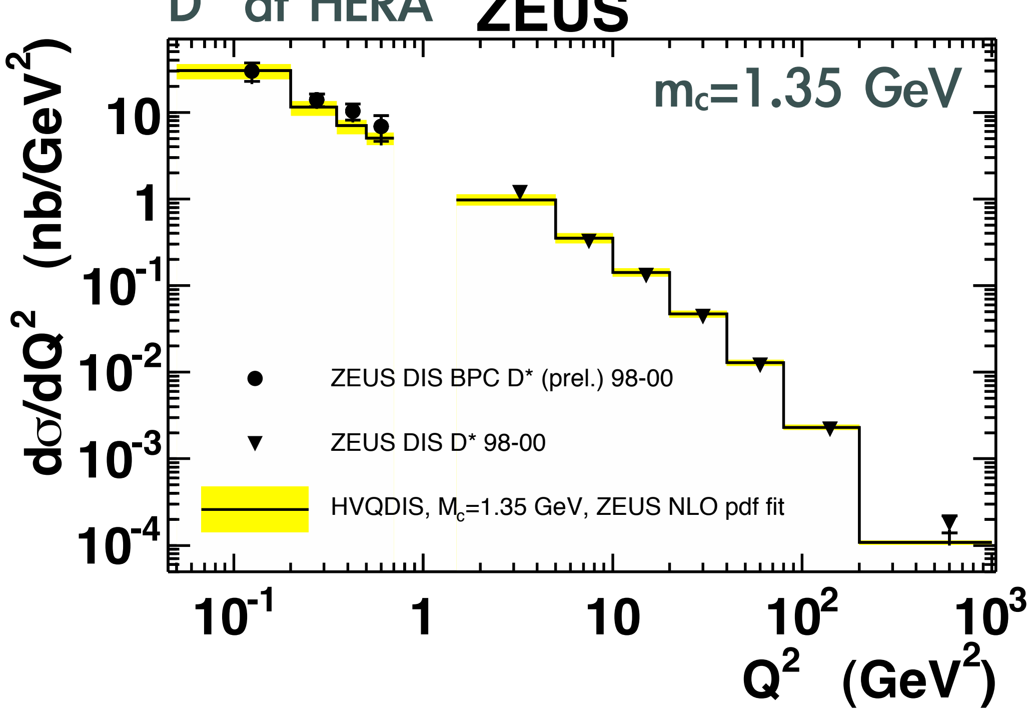
Recent developments:
- MC@NLO NLO+PS, hadron-level Monte Carlo (for $p\bar{p}$), S.Frixione, B.R.Webber, 2002
- NNLO predictions for $F_2^{cc}$ and $F_2^{bb}$ from fit to scaling violations R.Thorne, 2005

# Charm Cross Sections

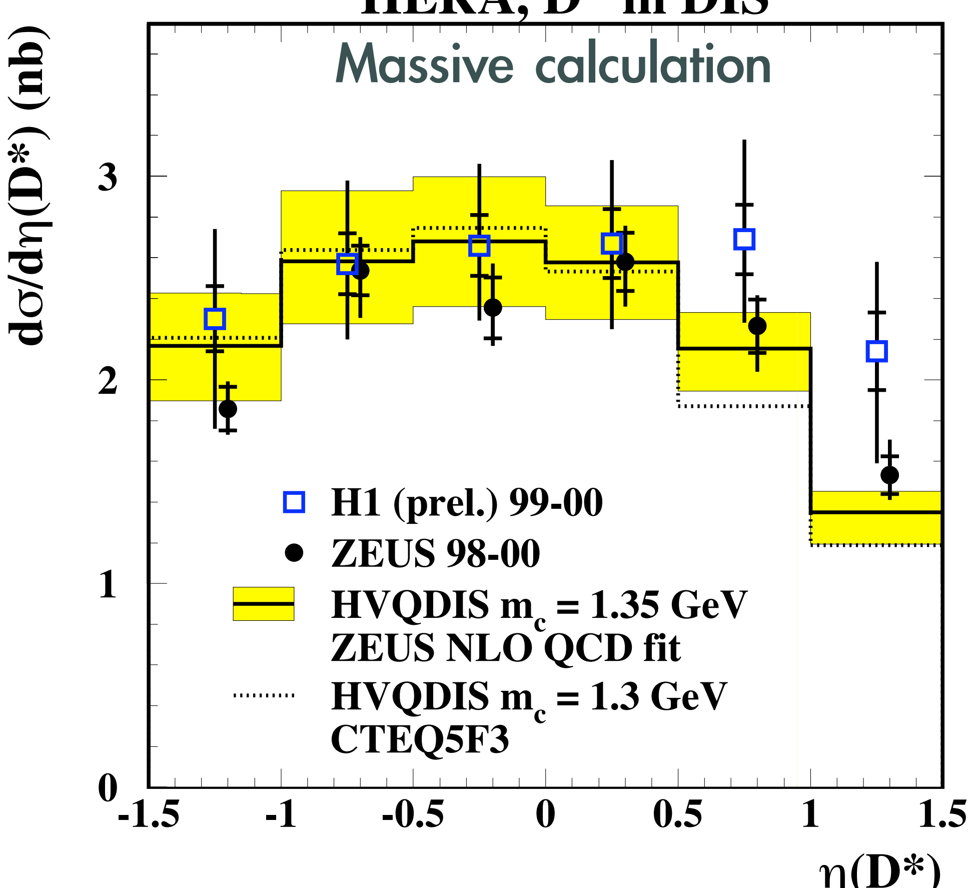
D* at Tevatron



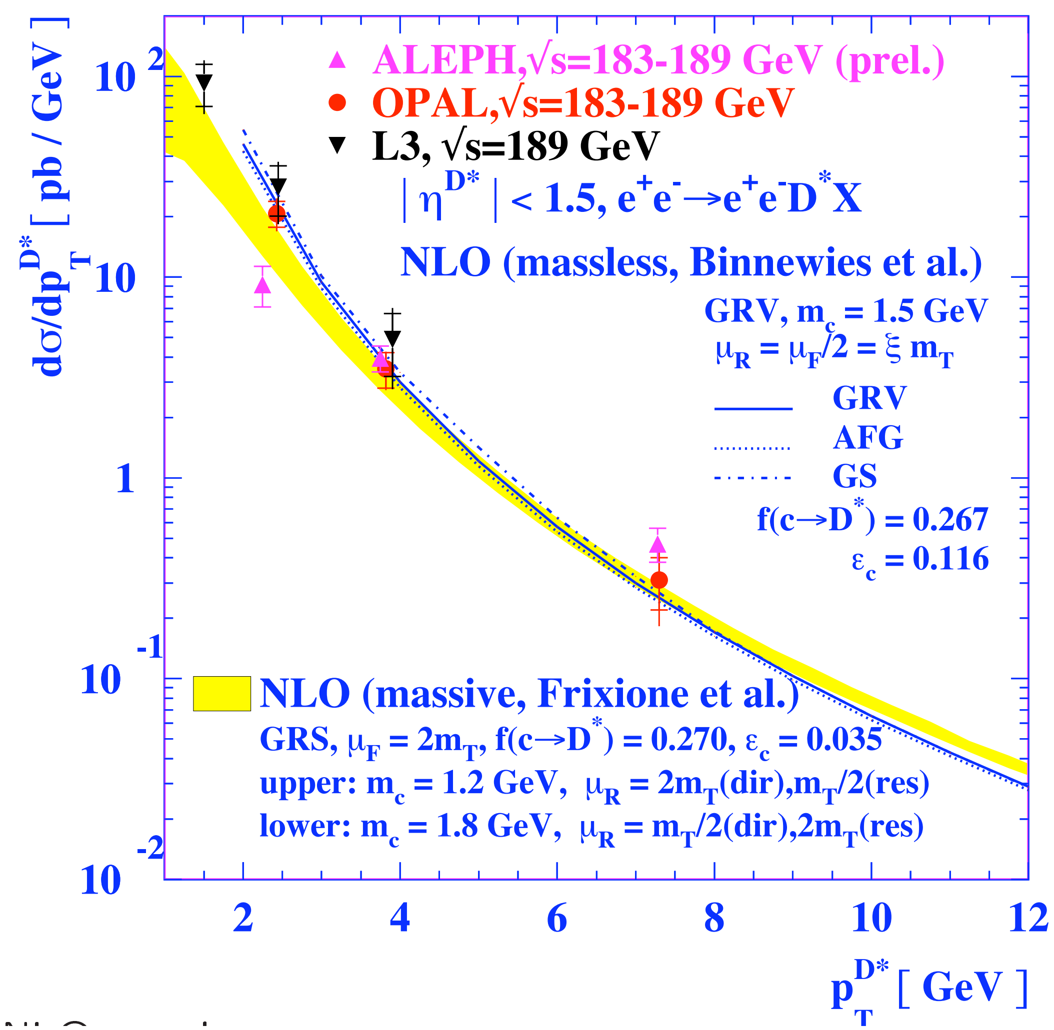

D* at HERA




Covering large range of photon virtuality $Q^2$



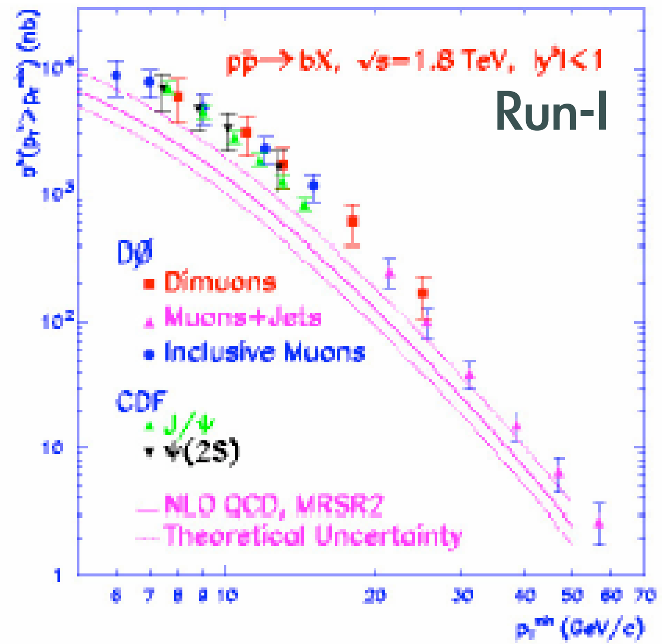

D* at LEP



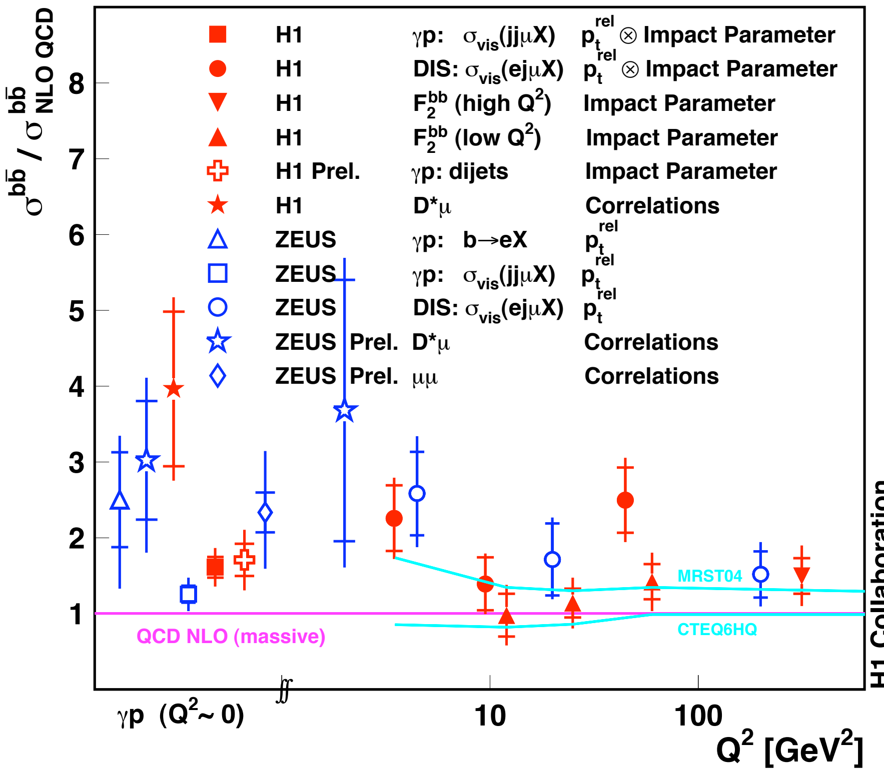

**NLO pQCD: Generally good description of inclusive charm**

**Large theoretical uncertainties, time to extract $m_c$ from data?**

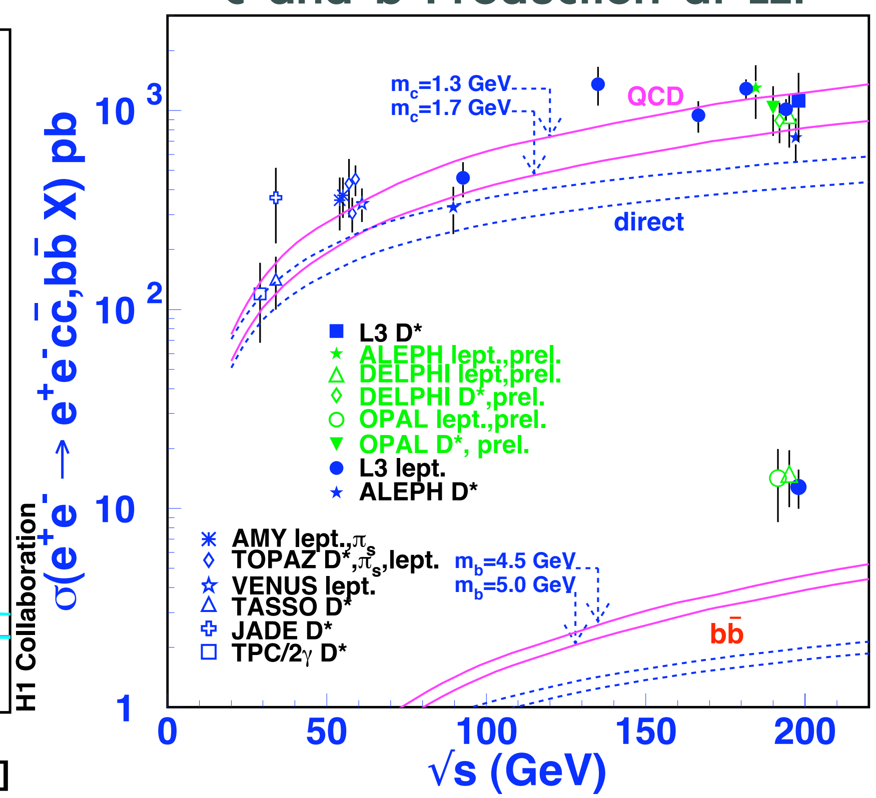
# Beauty Cross Sections

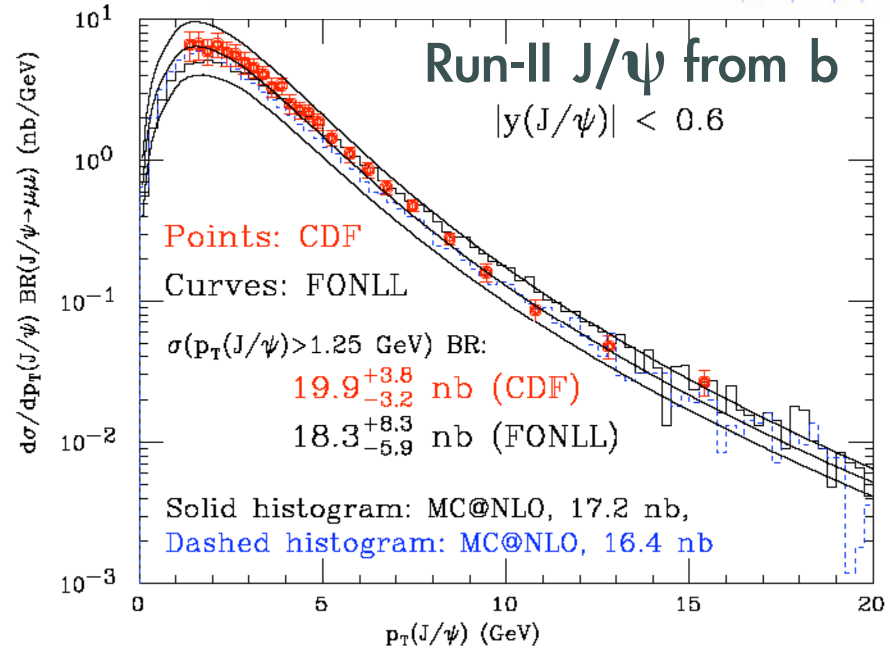



## Beauty Production at HERA




## c and b Production at LEP




**HERA:**

Many new measurements

Overall agreement between different measurements

General trend to be somewhat higher than massive NLO

**LEP:**

c ok, b significant excess

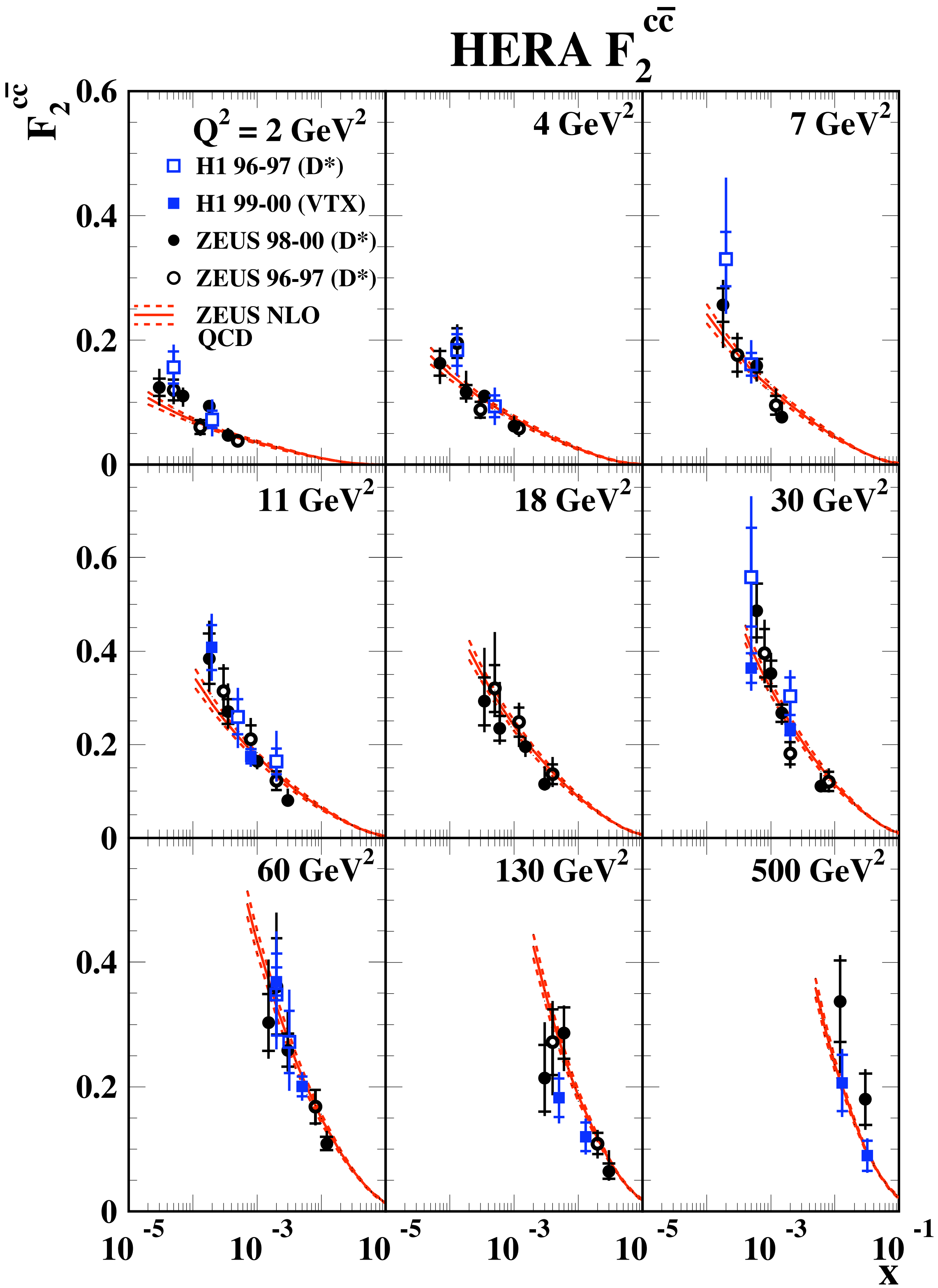
**Tevatron:**

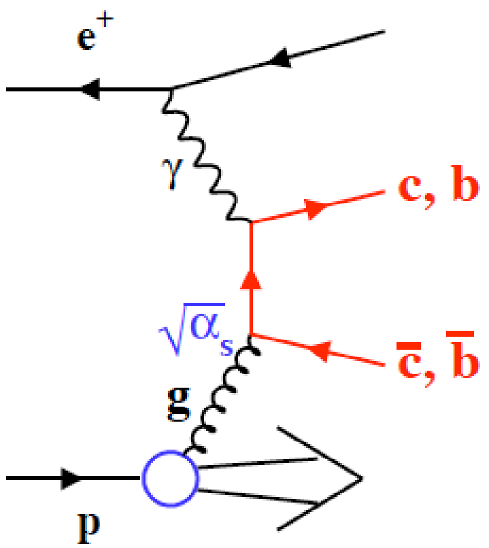
Very high statistics Run-II data

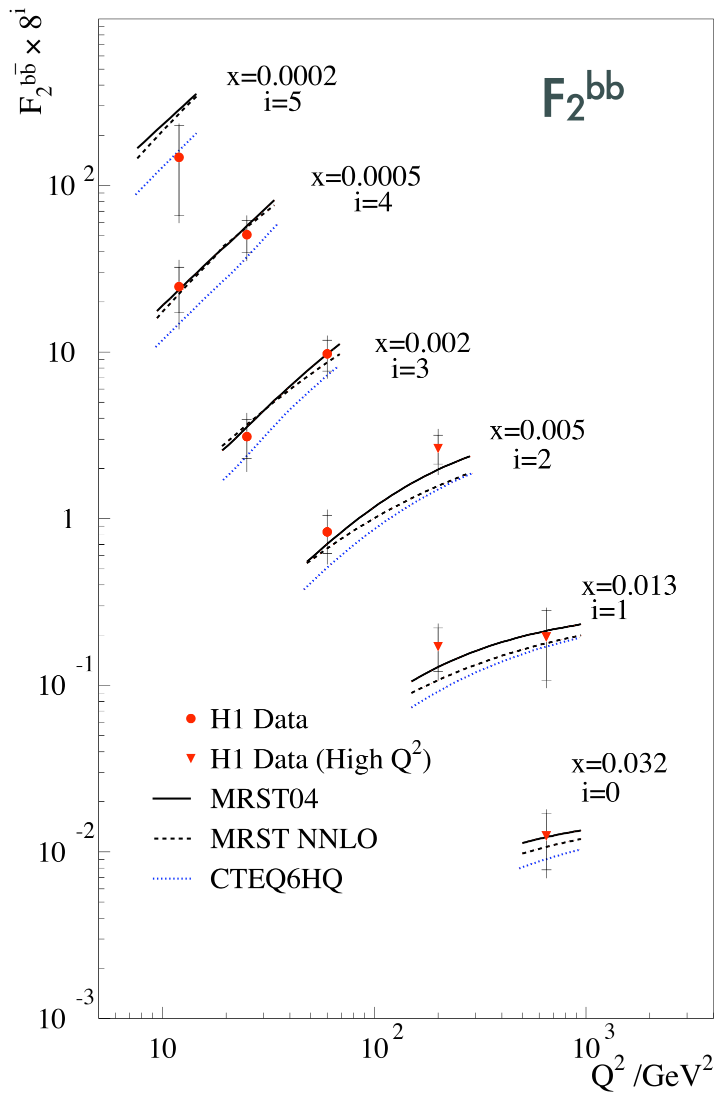
Theory improvements for pp̄ (FONLL and MC@NLO): mainly better treatment of fragmentation and hadronisation

Large differences between different QCD calculations

# Charm and Beauty Structure Functions




cf. P.Thompson

Very precise charm data
- using photon to probe proton structure
- confirming boson-gluon fusion picture
- starting to help constrain gluon distribution

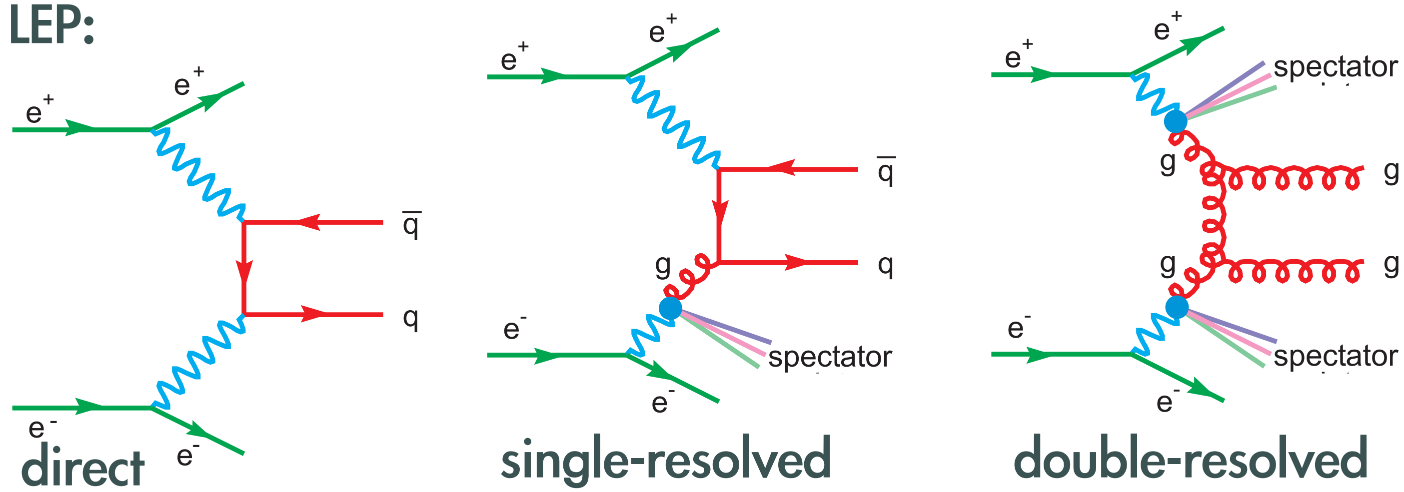
First determination of inclusive ep beauty cross section
- scaling violations seen
- ($F_2^{bb}$ e.g. required for LHC, $b\bar{b} \rightarrow H$)

# Photon Structure

## Photon reveals hadronic component

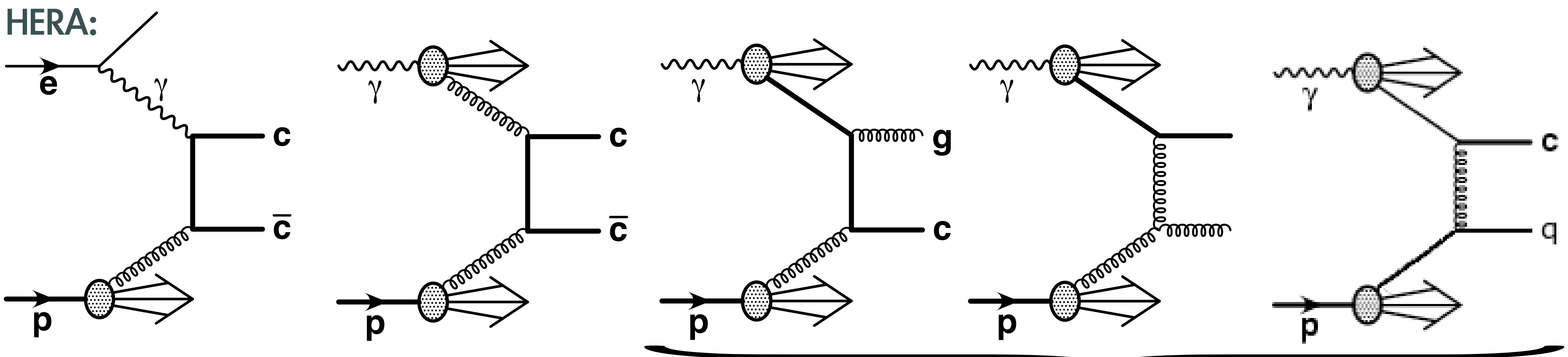
## Distinguish between direct and resolved contributions (leading order picture)

LEP:




direct | single-resolved | double-resolved

HERA:




Direct | hadron-like | c or b-excitation

(LO in massless, NLO in massive)

**HERA: Use proton to investigate photon: How much charm and beauty is there in the photon?**

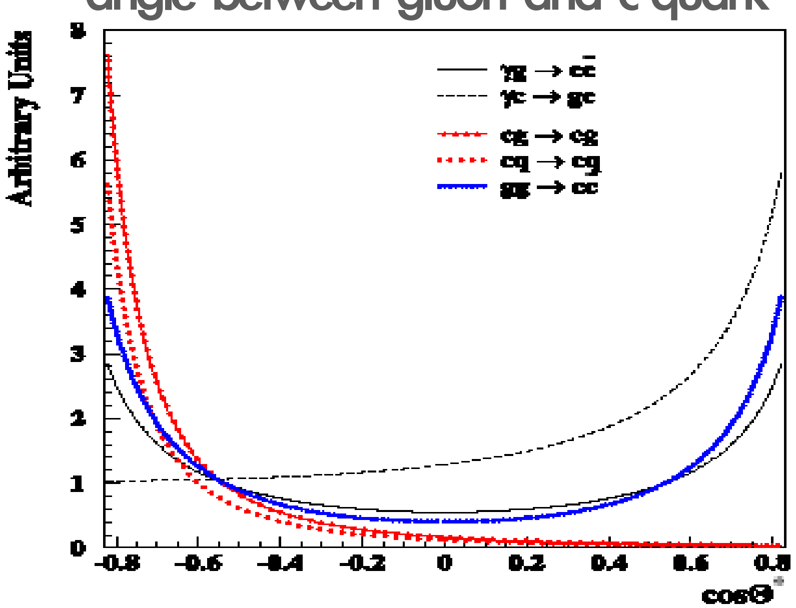
# Charm in the Photon

Distinguish direct and
various resolved contributions

In charmed di-jet events reconstruct momentum
fraction of parton from photon side:

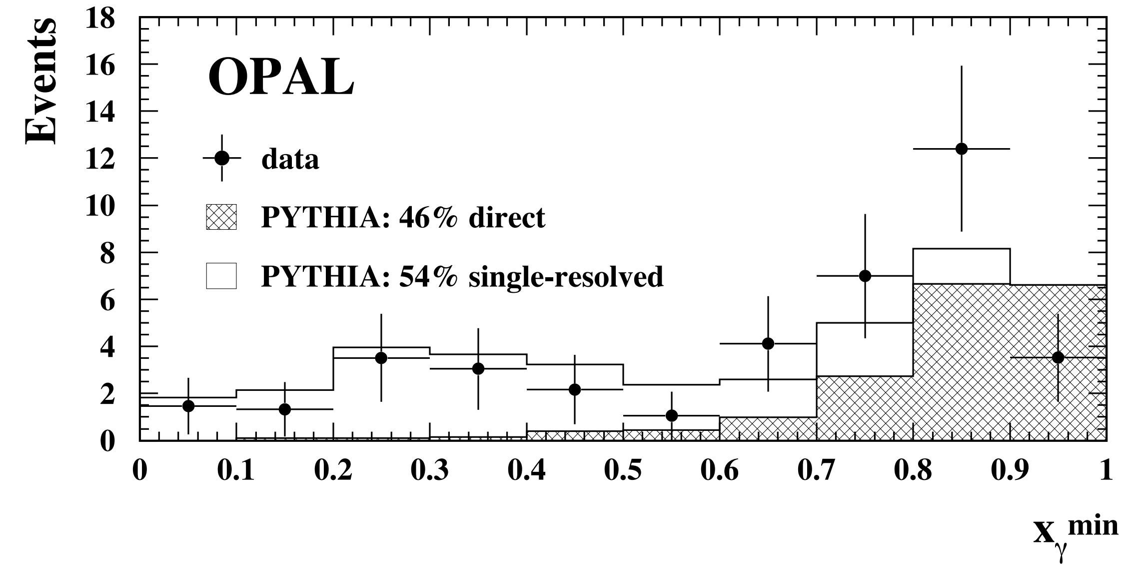
$$x_\gamma^{obs} = \frac{\sum_{j_1,j_2}(E_t^j e^{-\eta^j})}{2yE_e}$$

angle between gluon and c-quark

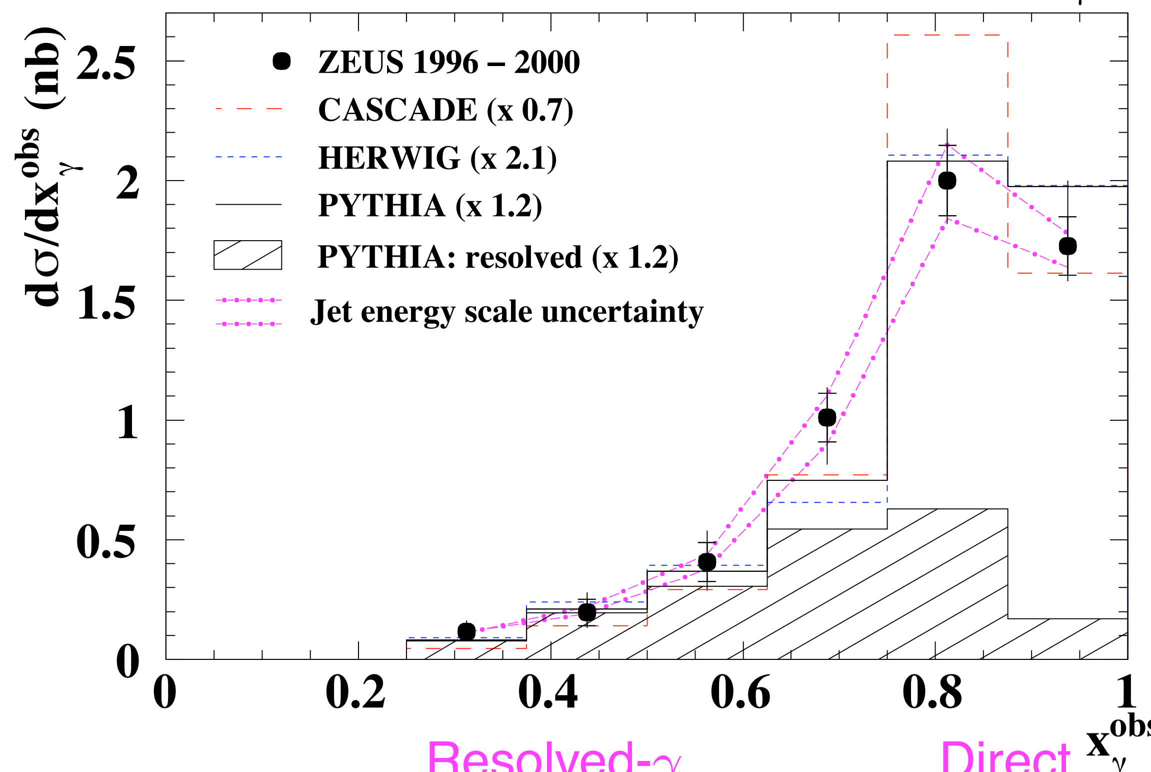



Different angular dependences for
different resolved components

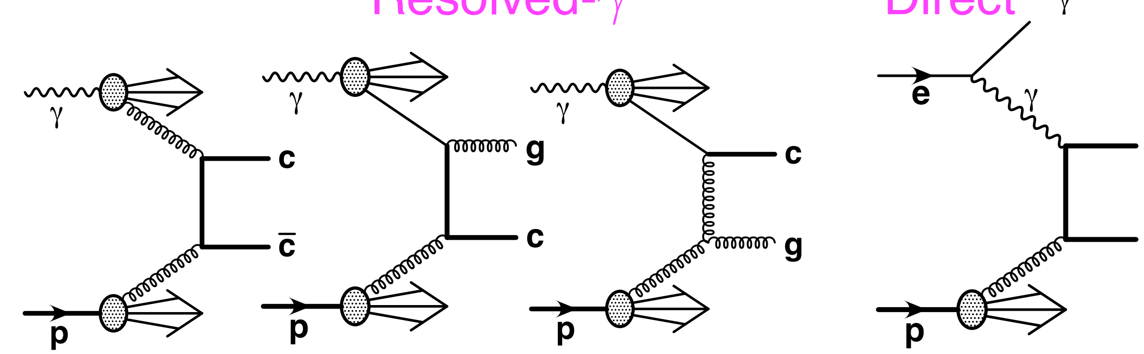
LEP




HERA

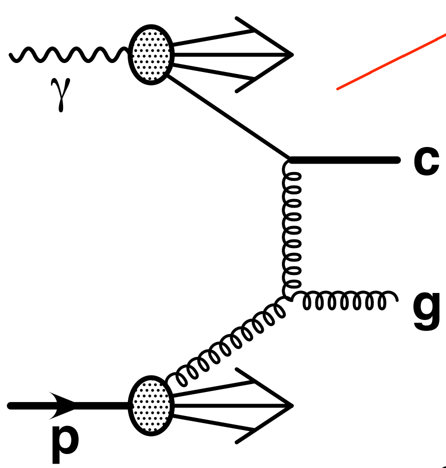


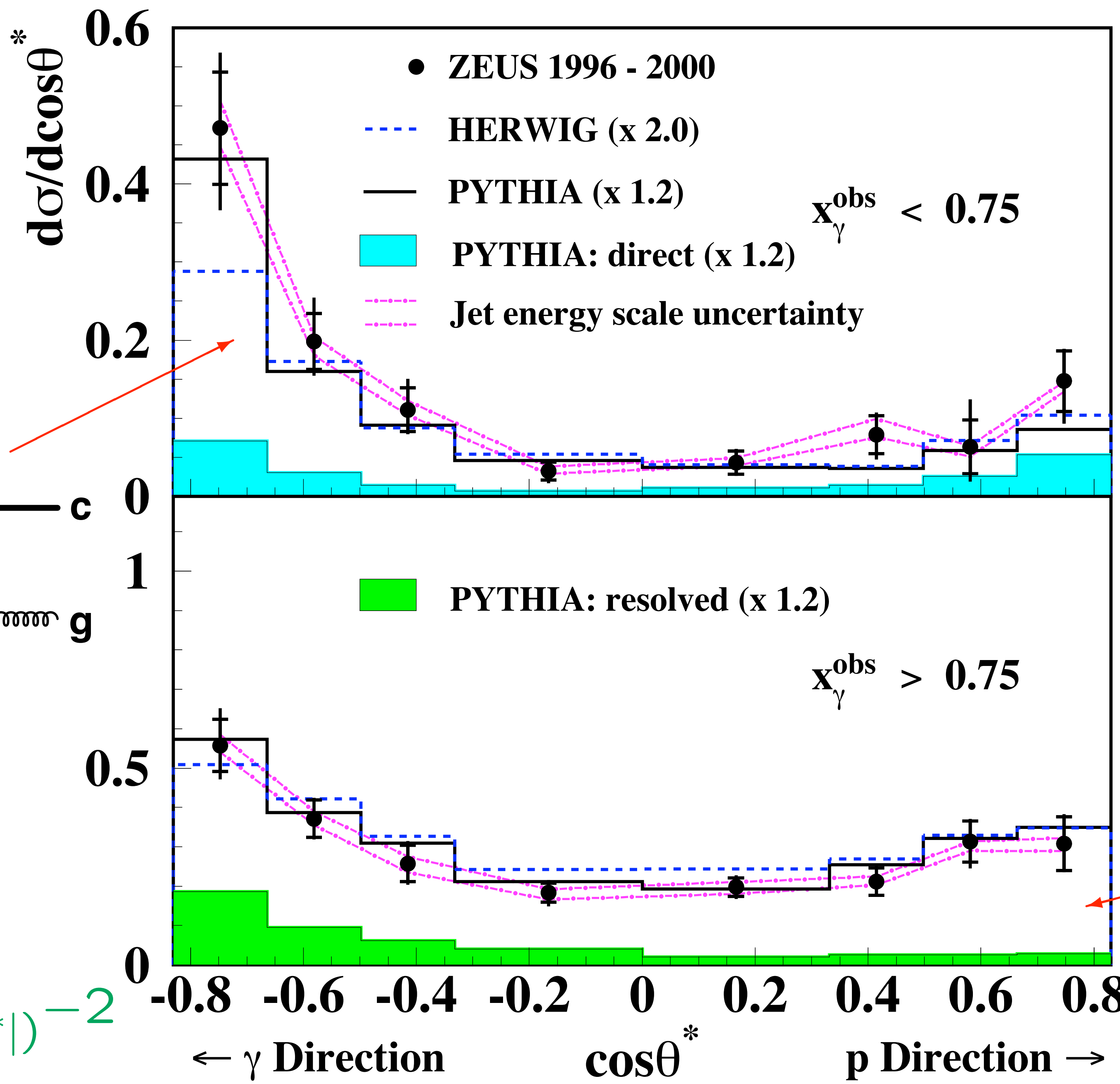

Resolved-$\gamma$ Direct



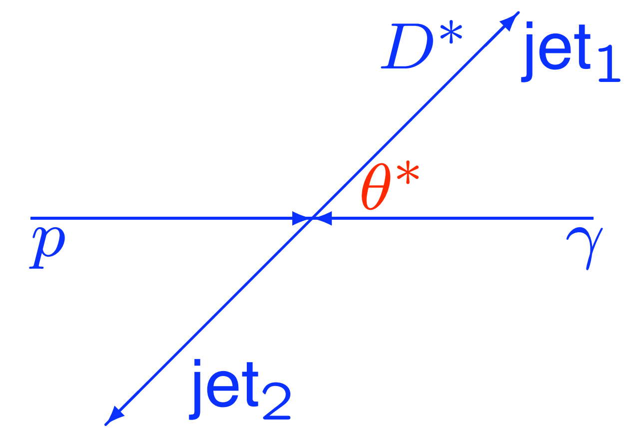

Large fraction of charm from resolved photons

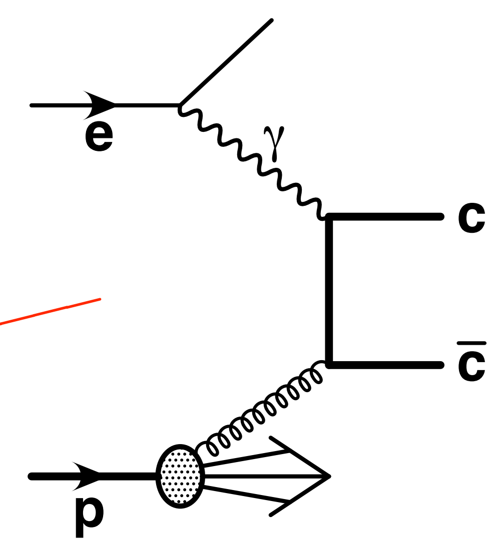
# Angular D*-Jet Distributions




$\theta^* = \measuredangle(p, D^*\text{-Jet})$:




$g$-Exchange:

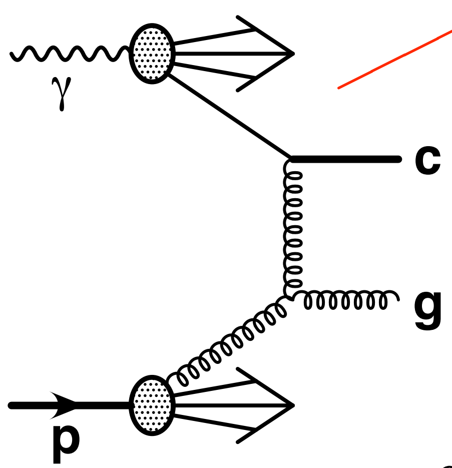
$\propto (1 - |\cos\theta^*|)^{-2}$

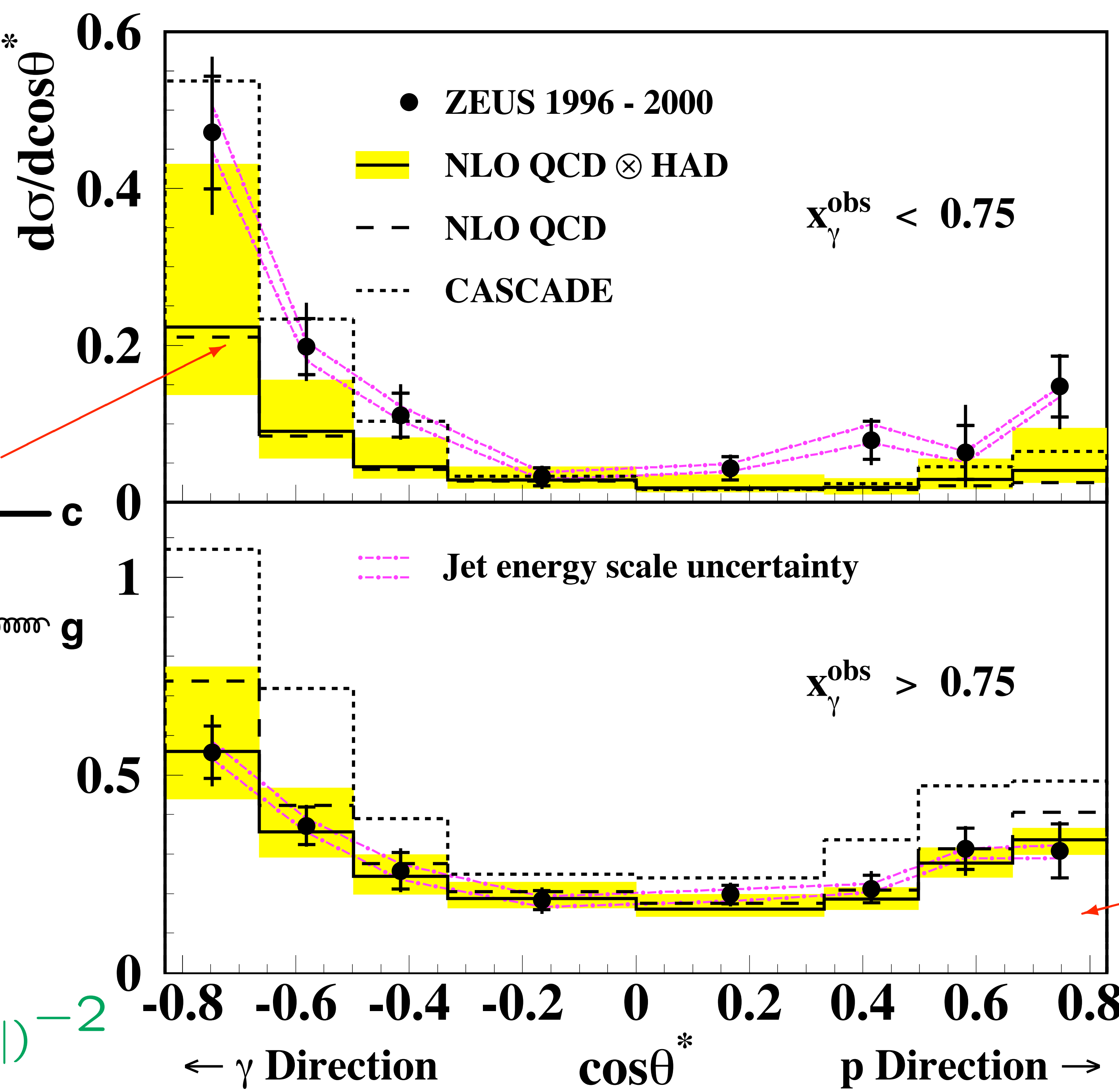
$q$-Exchange:

$\propto (1 - |\cos\theta^*|)^{-1}$

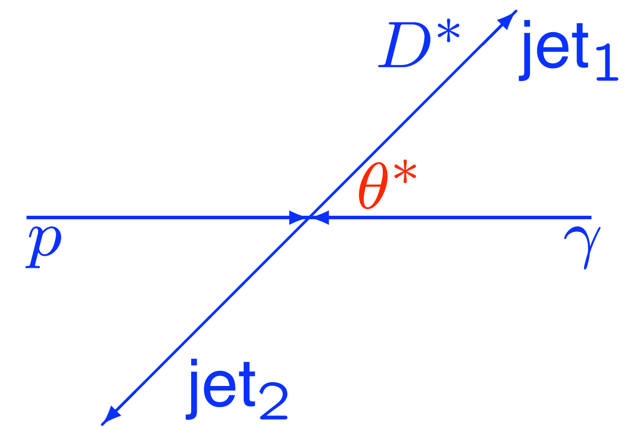
D* in photon direction: Charm coming from photon
Increase in photon direction: gluon exchange signature

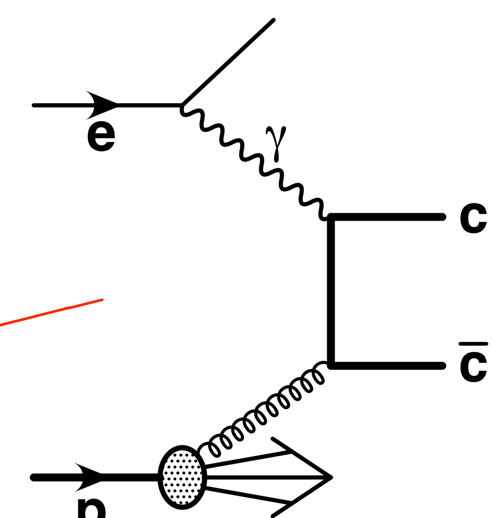
# Angular D*-Jet Distributions




$\theta^* = \measuredangle(p, D^*\text{-Jet})$:



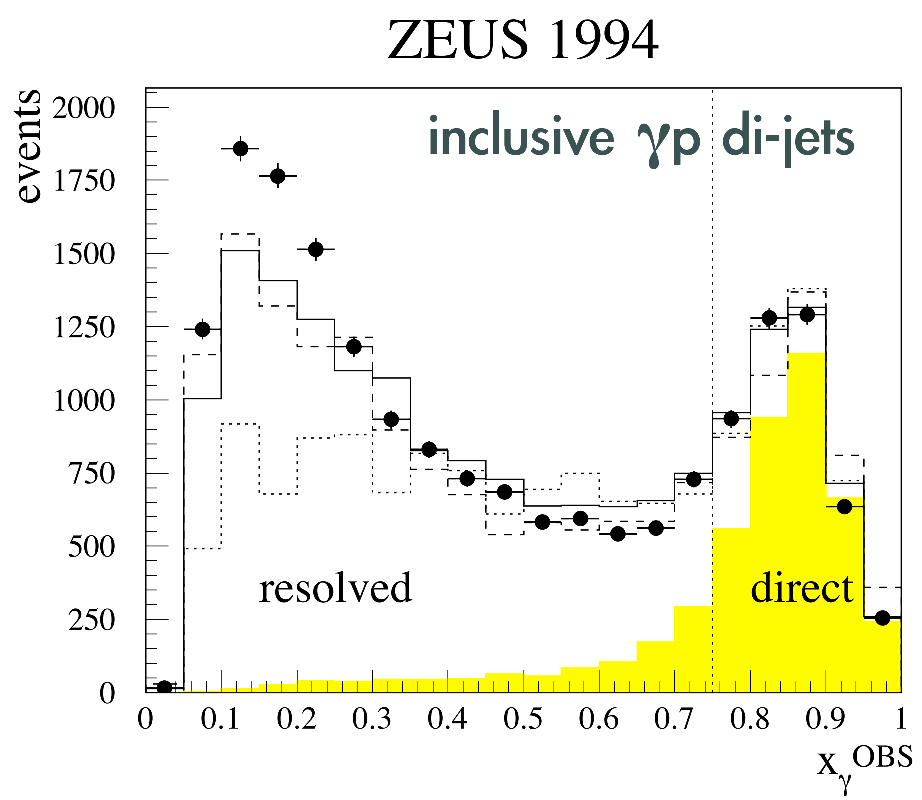

$g$-Exchange:
$\propto (1 - |\cos\theta^*|)^{-2}$

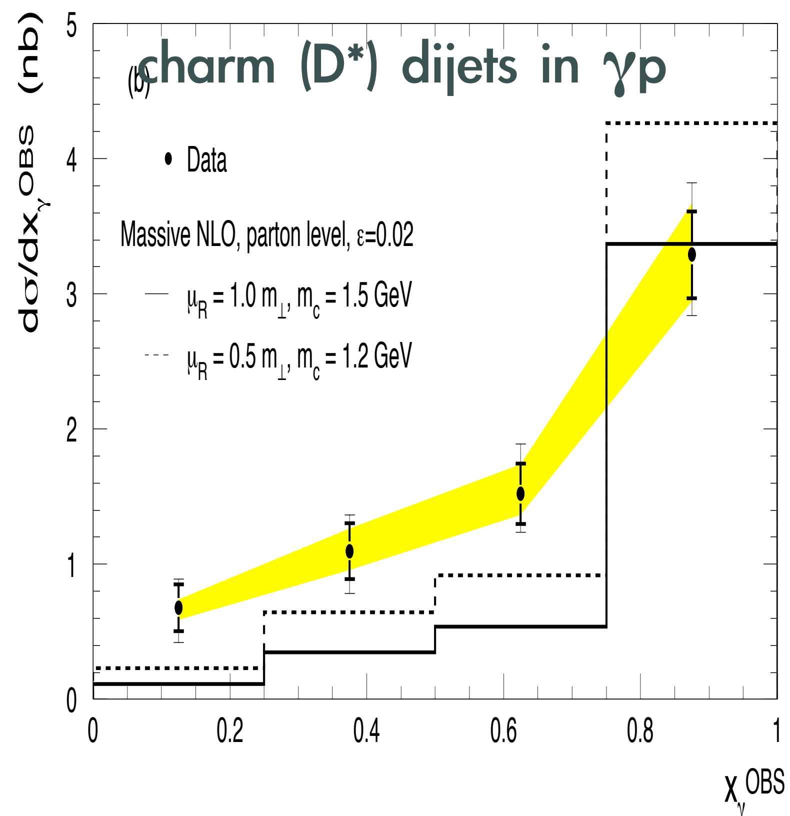
$q$-Exchange:
$\propto (1 - |\cos\theta^*|)^{-1}$

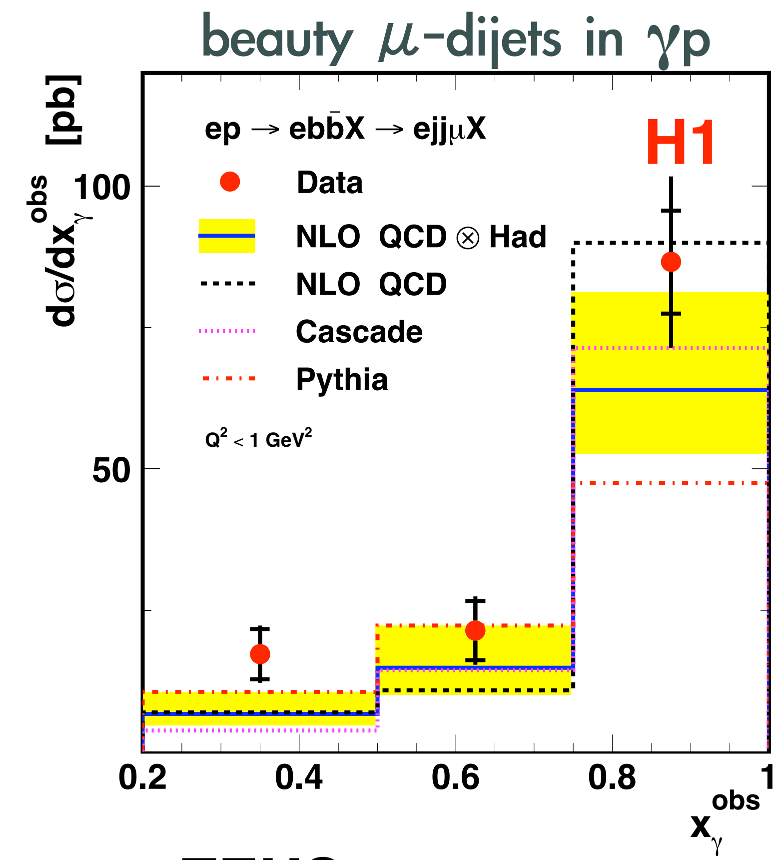
NLO Calculation: Describing data w/o explicit c-excitation contribution (however, somewhat low at $x_\gamma$<0.75)

# Resolved Photons vs. Scale

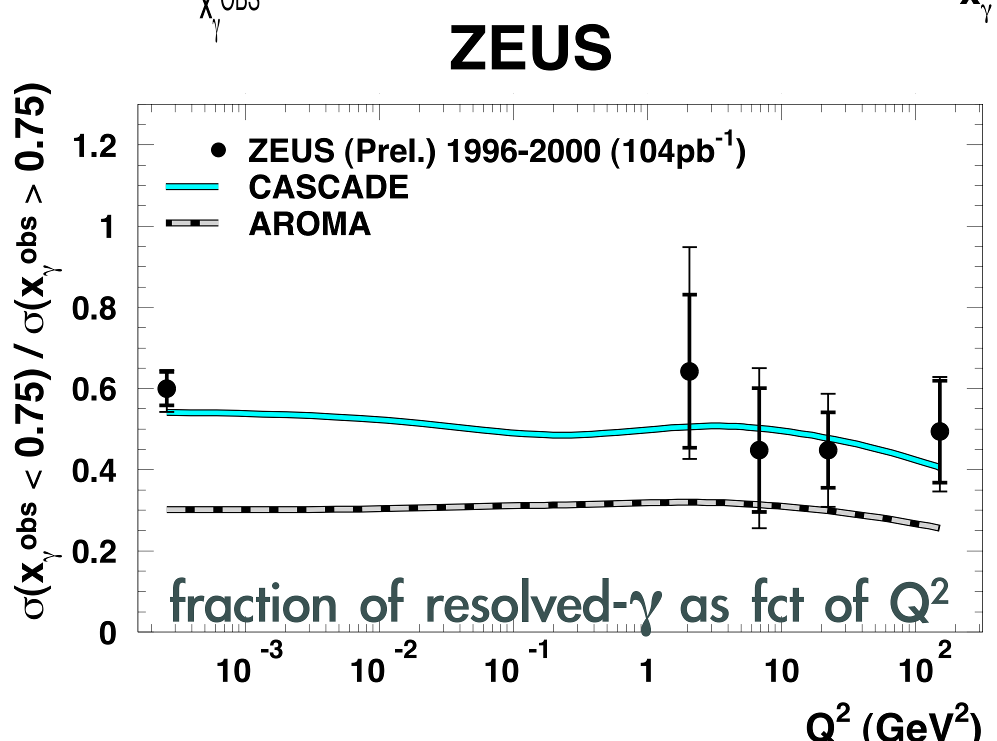
Compare light quark, charm and beauty in resolved di-jet photoproduction
(note different but comparable di-jet cuts for inclusive, c and b)




Resolved component appears to decrease with increasing quark mass (hard scale)

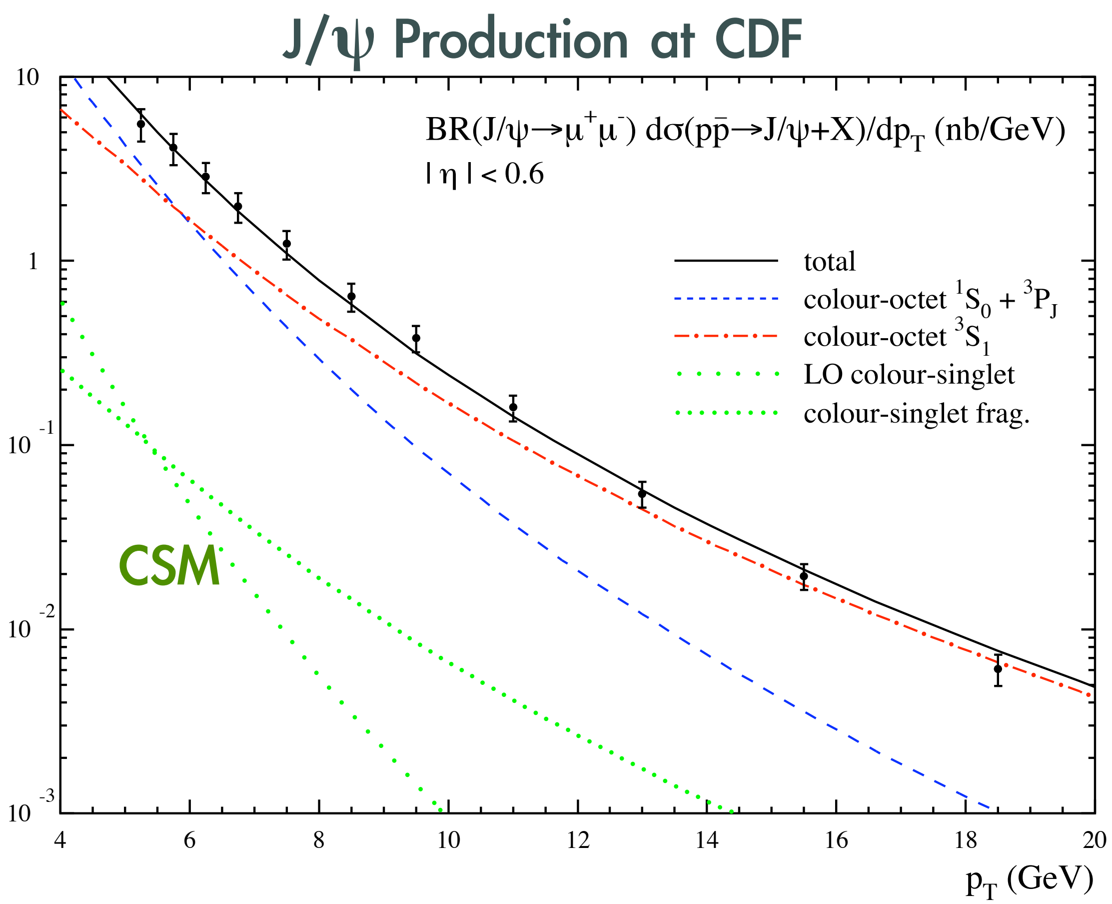



Alternative scale: $Q^2$

Measure charm in resolved virtual photons

First measurements indicate little suppression with $Q^2$
Need more statistics for better precision (HERA-II)

# Charmonium Production



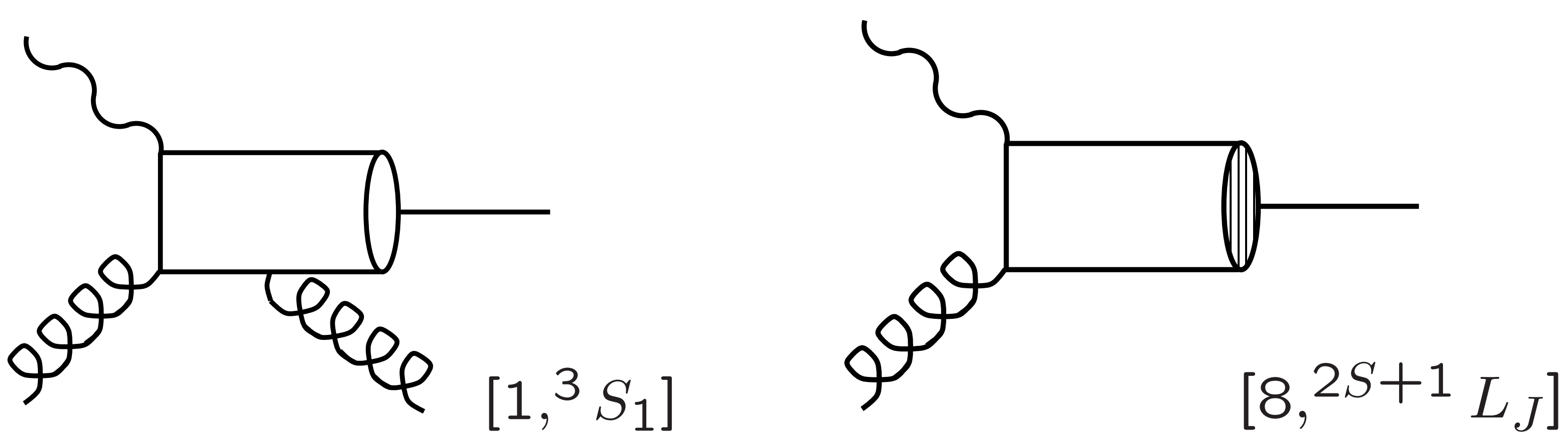

pp̄: CS (LO) factor ~30 lower than data !

**NRQCD-factorization:**

$$\sigma_{J/\psi X} = \sum \hat{\sigma}(p\bar{p} \to c\bar{c}[n]X) \times \text{LDME}[n]$$

Long distance matrix elements (LDME) from NRQCD fits to Tevatron data

Assume/test universality of LDME data from other experiments (e.g. HERA, LEP, b-factories)



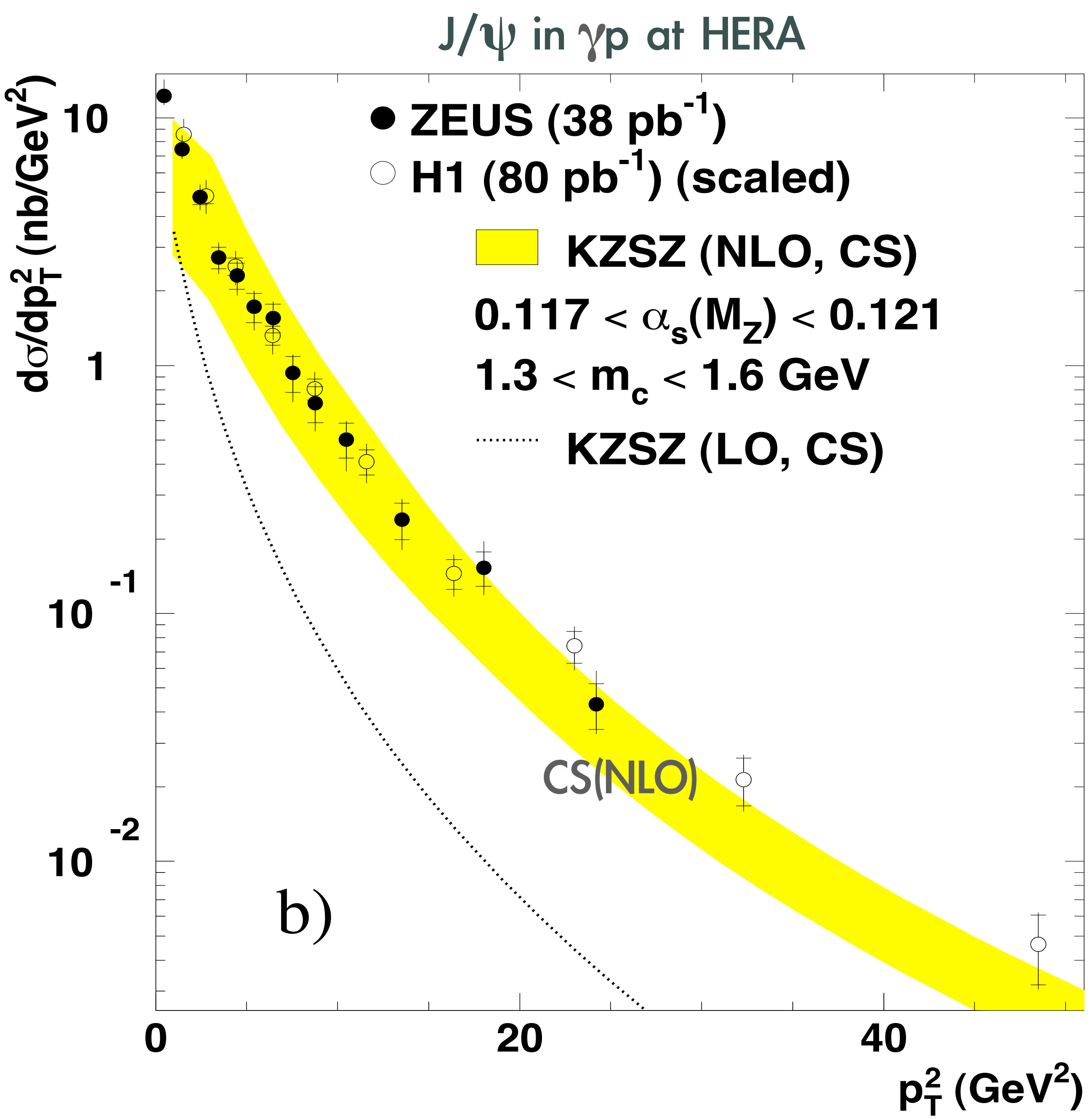

Colour Singlet (CS)
$c\bar{c} \to J/\psi$ + gluon

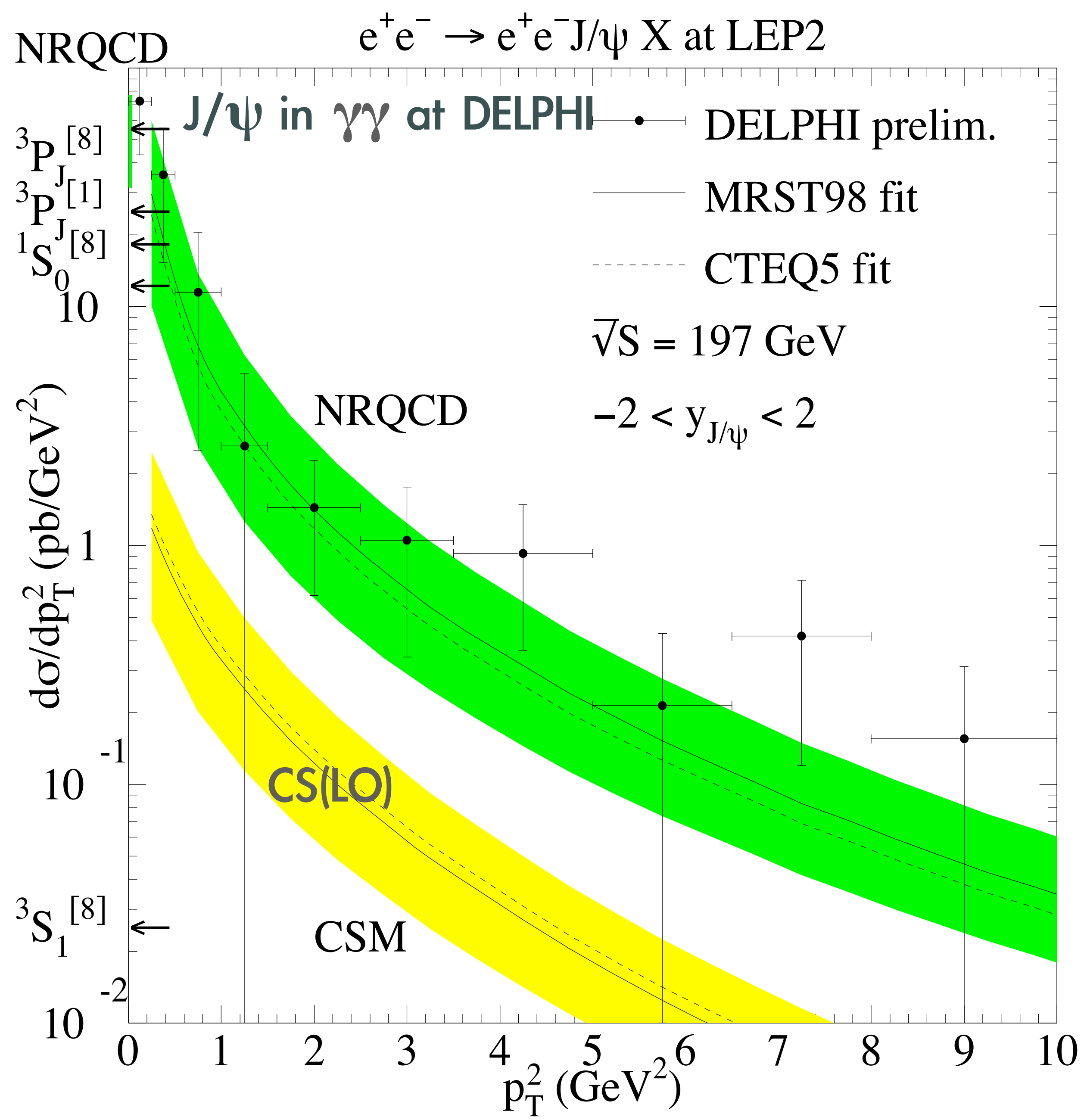
Colour Octet (CO)
$c\bar{c} \to J/\psi$ + soft gluons

Note:
NRQCD is LO only,
NLO underway

NLO only available for Color Singlet in $\gamma p$

# Charmonium Production in γp and γγ



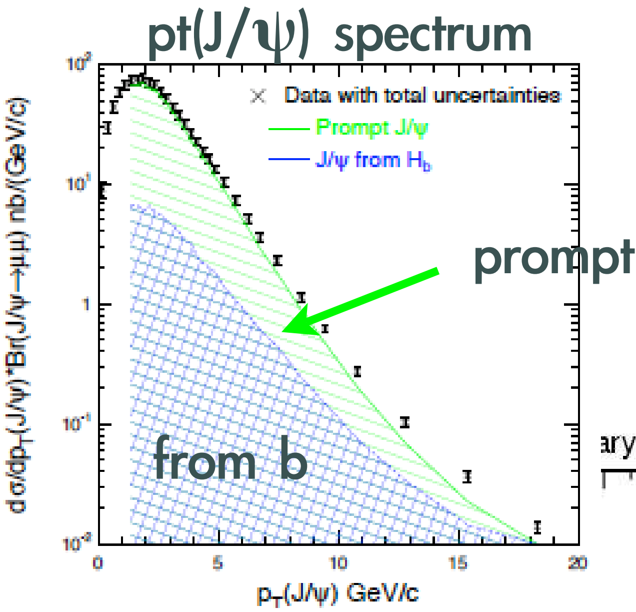

γp: CS (NLO) alone describes data

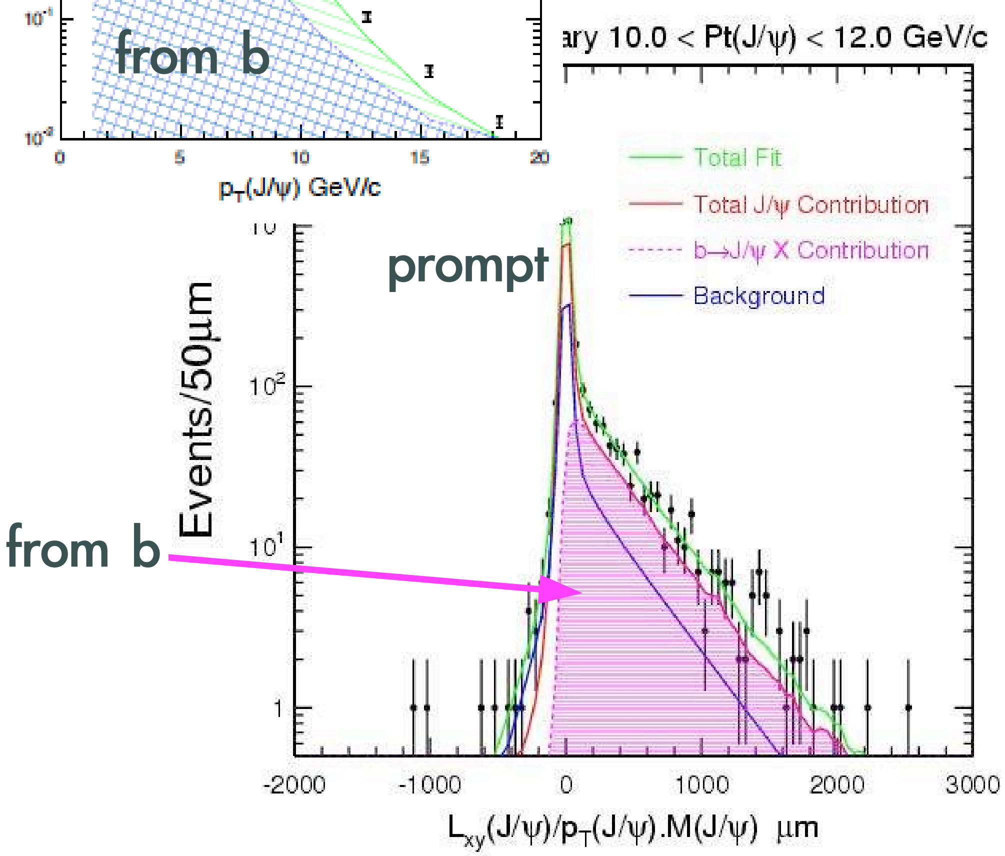
γγ: NRQCD ok, CS (LO too low)

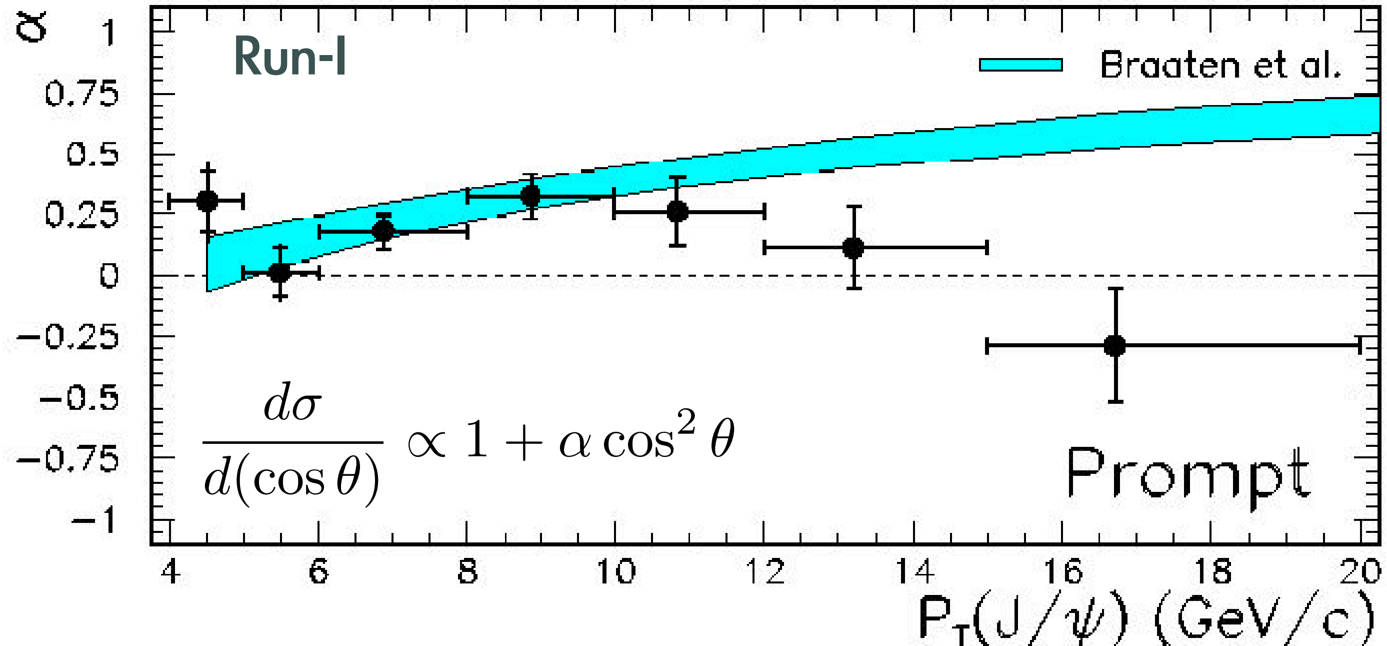
# J/ψ Polarisation

THE smoking gun signature for NRQCD

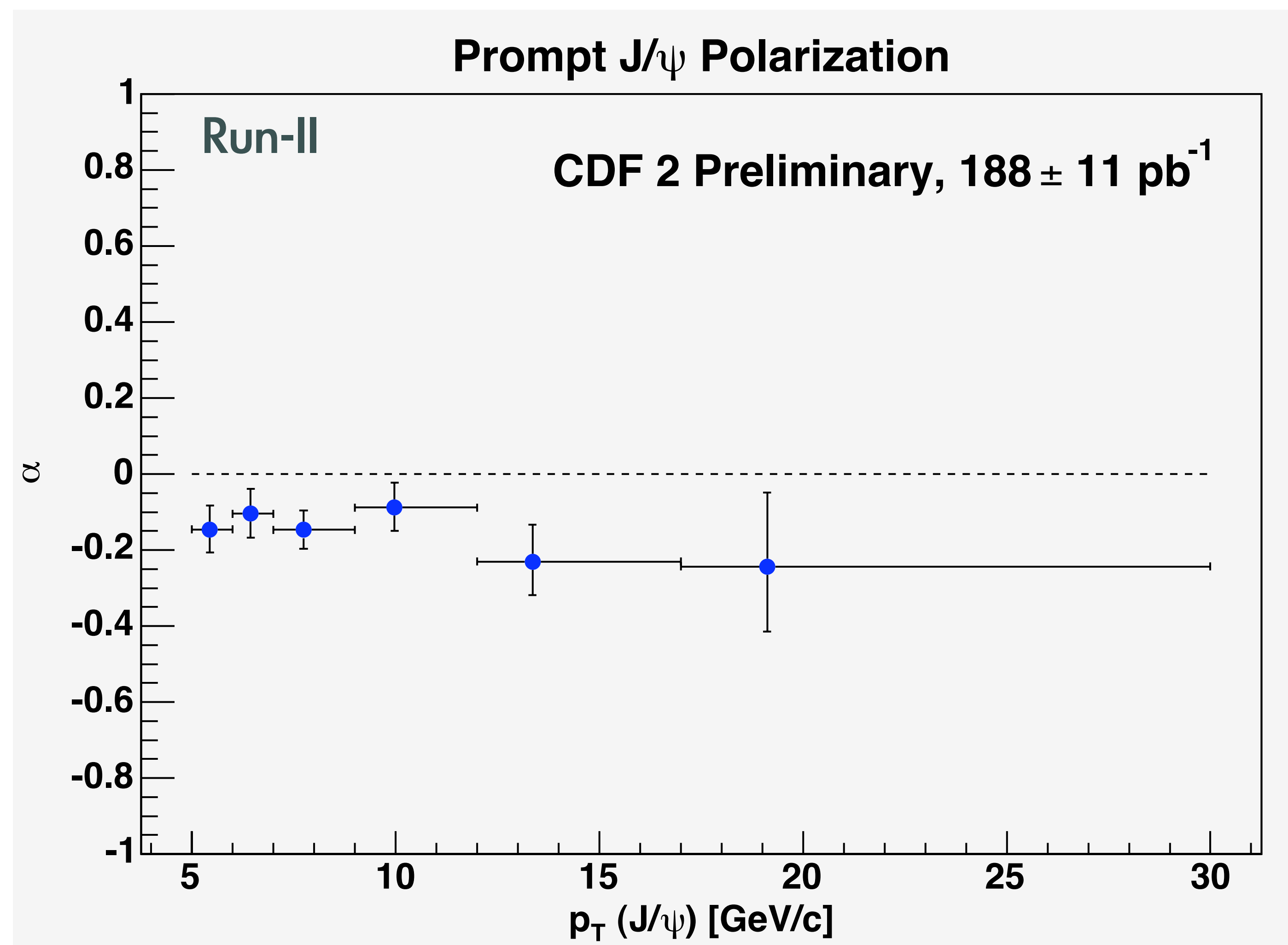
Select prompt component of
J/ψ sample using lifetime spectrum




Transverse polarization from g-fragmentation

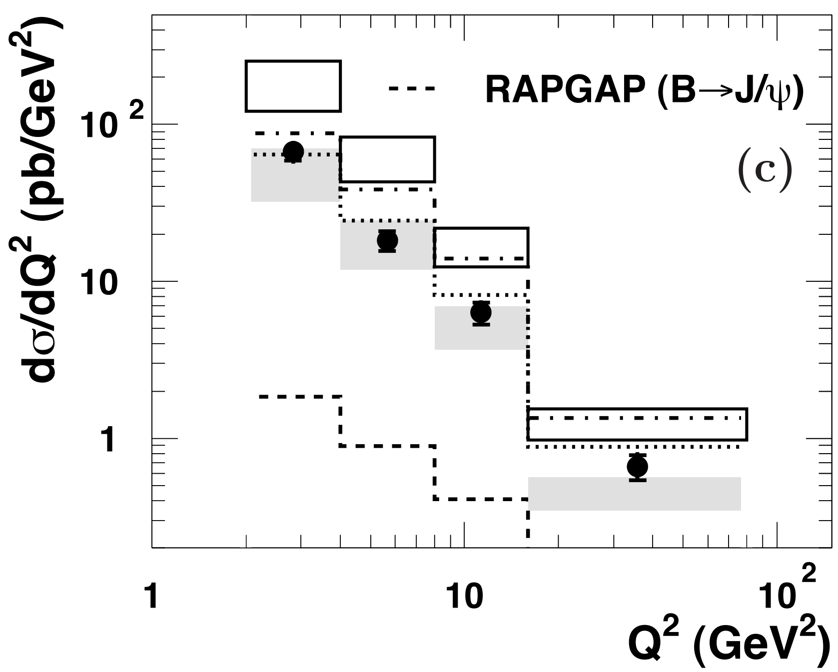


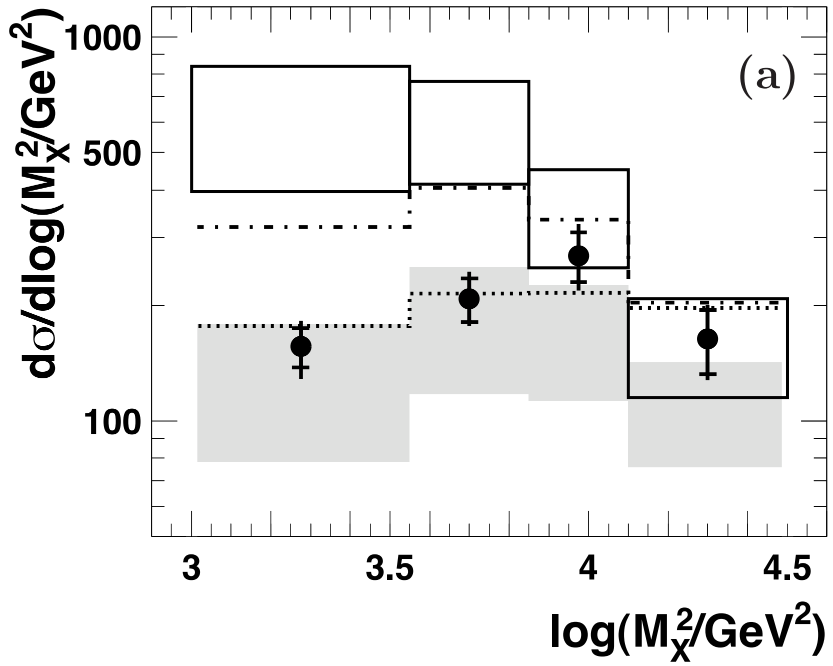

Both Run-I and Run-II in contradiction to NRQCD

# Charmonium production at HERA

## New measurement from ZEUS:

(kinematic range: $2<Q^2<80$ GeV$^2$, $50<W<250$ GeV, $0.2<z<0.9$, $-1.6<Y_{lab}<1.3$)



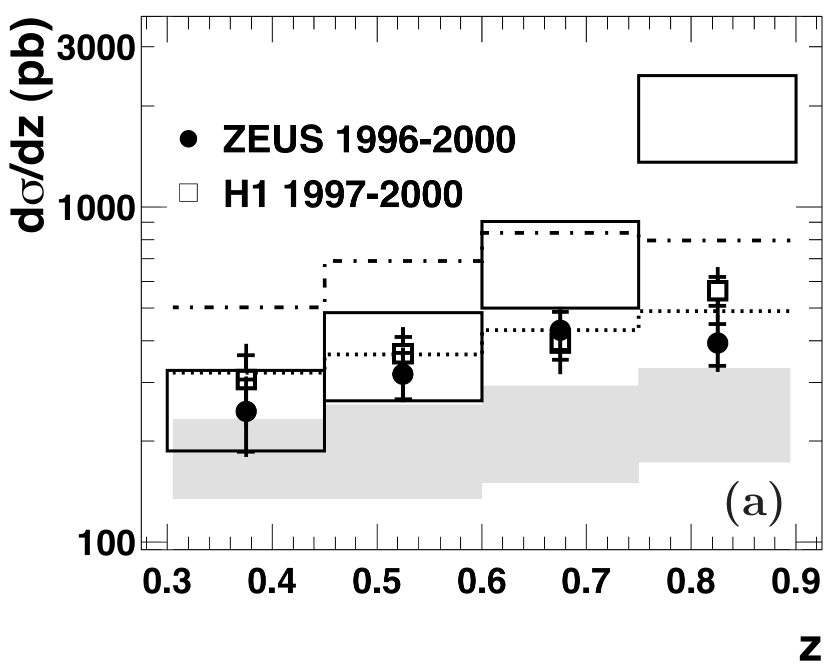



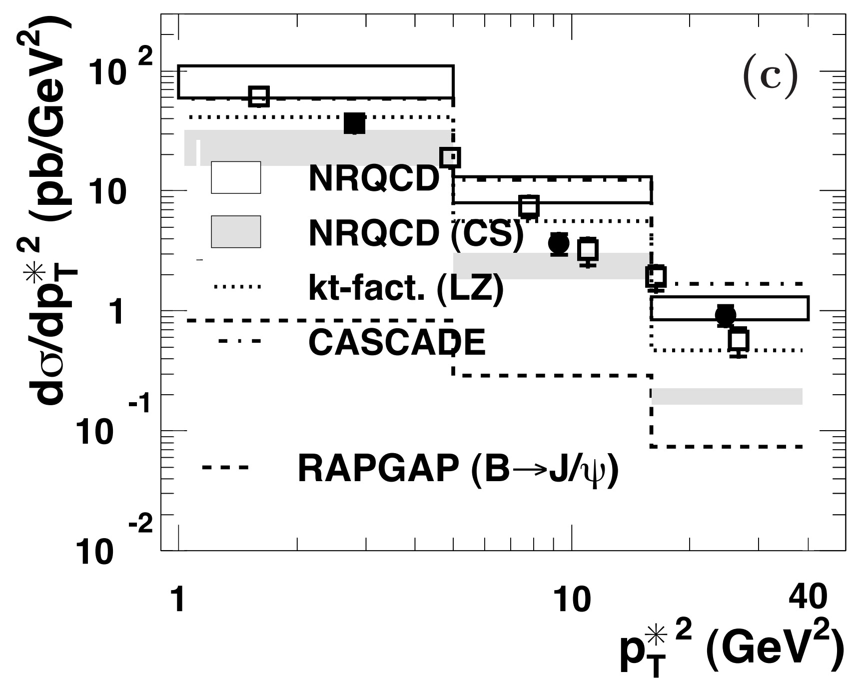

Good agreement:

CS models (LO) alone (both DGLAP and CCFM)

Full NRQCD (LO) too high

## Additional cut on $p_t^* > 1$GeV (compare with H1, remove regions of largest theor. uncertainty)



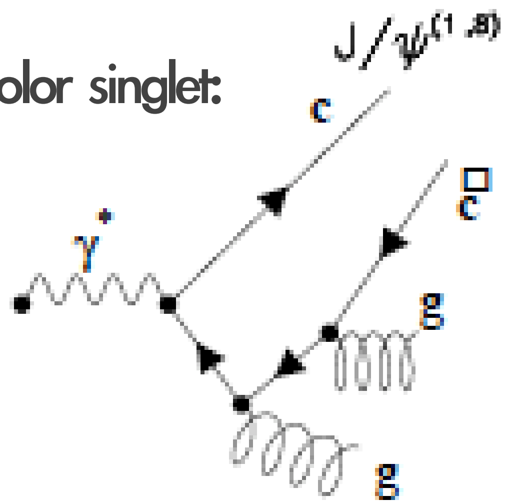

ZEUS consistent with H1

CS: slight deficiency in norm.

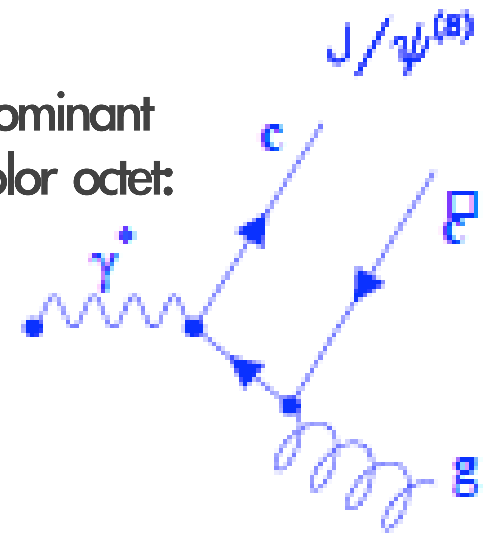
NRQCD (LO) too high at high z

# Charmonium at b-Factories

Color singlet:



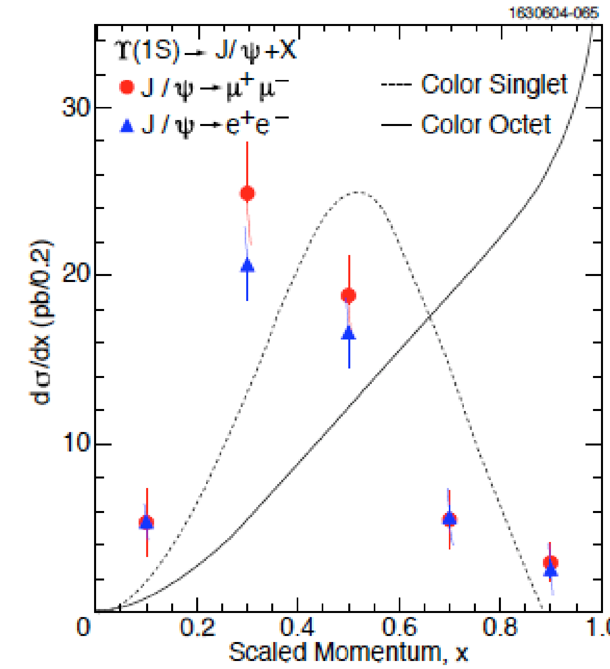

Dominant color octet:



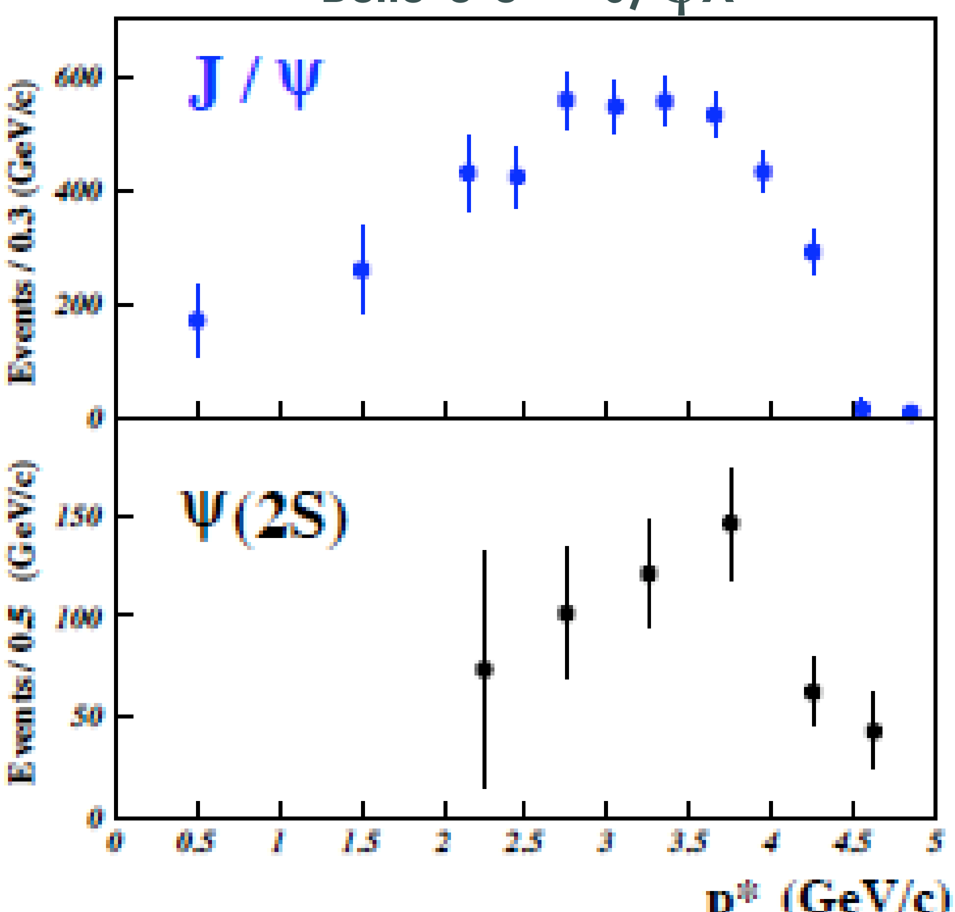

singularity at large z, (as for NRQCD at HERA)

gluon resummation to describe data at endpoint

CLEO Υ(1S)→J/ψX continuum subtracted

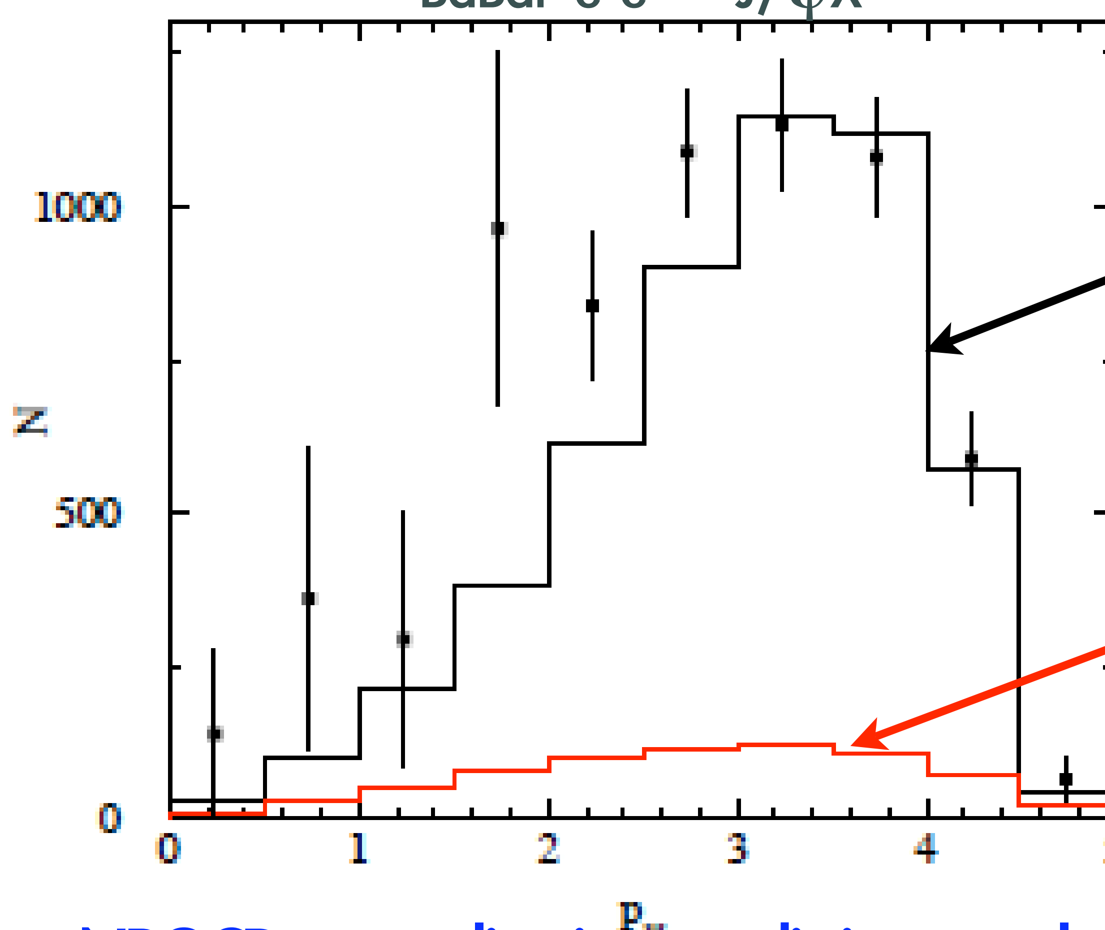



Belle $e^+e^- \to J/\psi X$




data falling towards p* endpoint

BaBar $e^+e^- \to J/\psi X$



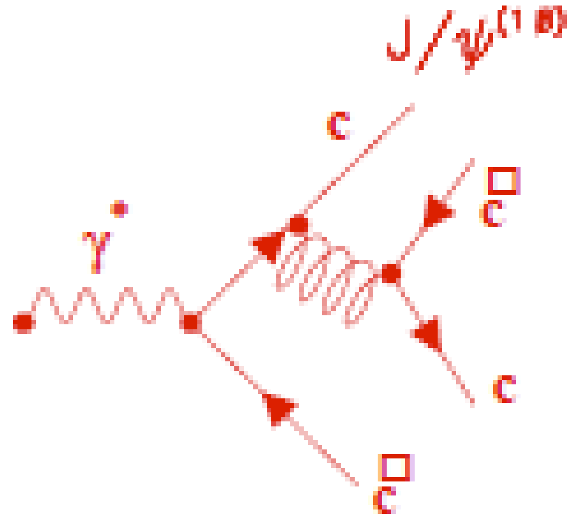

resummed NRQCD (normalised to data)

CSM (absolute normalization)

NRQCD normalization prediction: too low (not shown)

# Double $c\bar{c}$ Production

$c\bar{c}c\bar{c}$ production:



**NRQCD Expectation:**

$\sigma(e^+e^- \to J/\psi\ c\bar{c})/\sigma(e^+e^- \to J/\psi\ X) = 10\%$

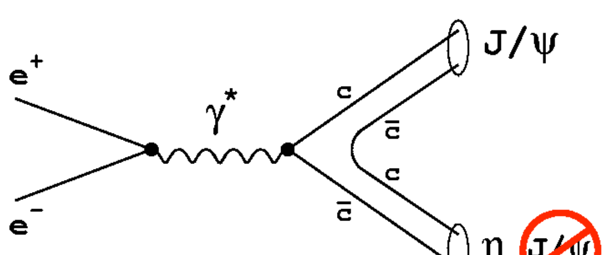
**Measurements:**

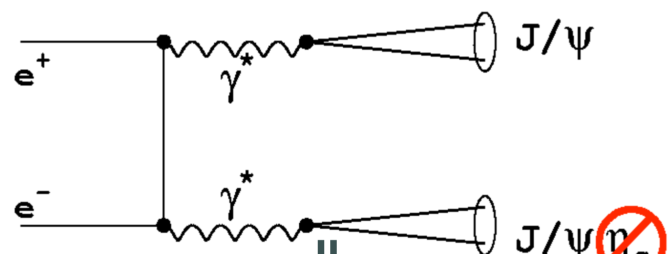
$\sigma(e^+e^- \to J/\psi\ c\bar{c})/\sigma(e^+e^- \to J/\psi\ X) = 60\% \pm 20\%$

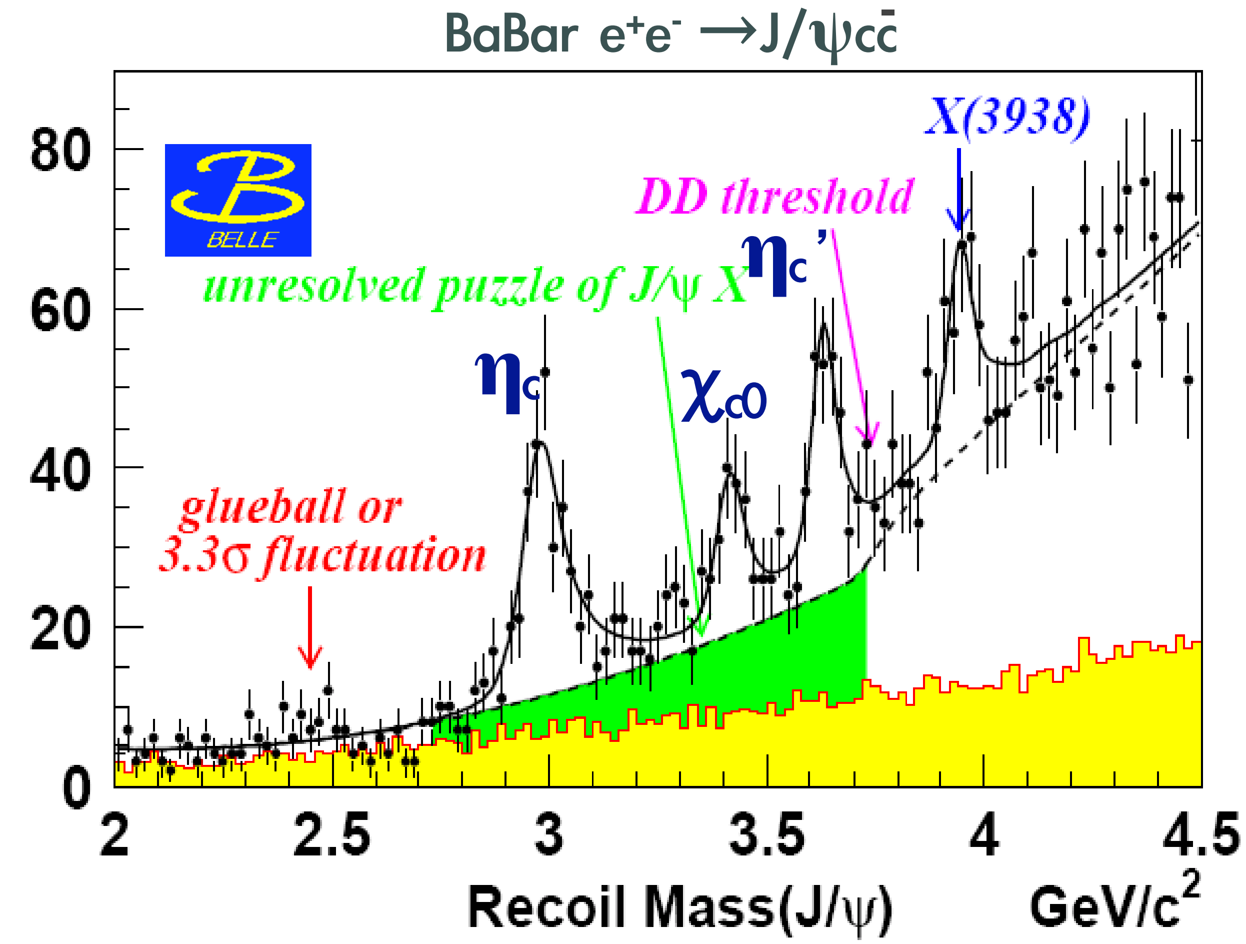
clear $\eta_c$, $\chi_{c0}$ & $\eta_c'$ signals, no $J/\psi$, $\psi(2S)$ etc.

$\sigma(e^+e^- \to J/\psi\ \eta_c) > 10 \times$ NRQCD prediction

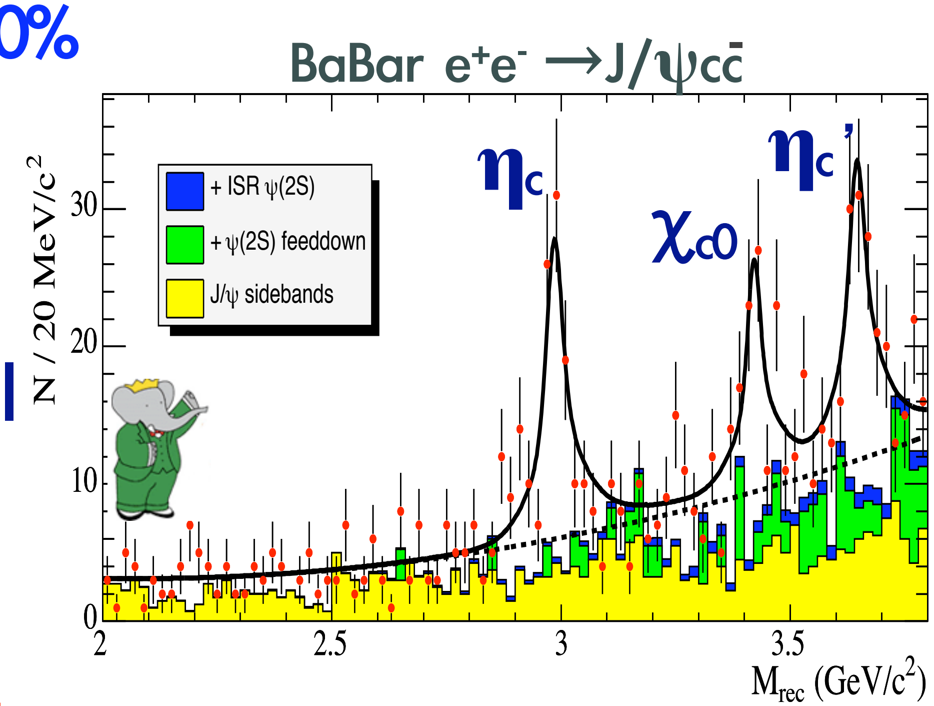
$e^+e^- \to \gamma \to J/\psi + J/\psi$ contribution is small


large


small

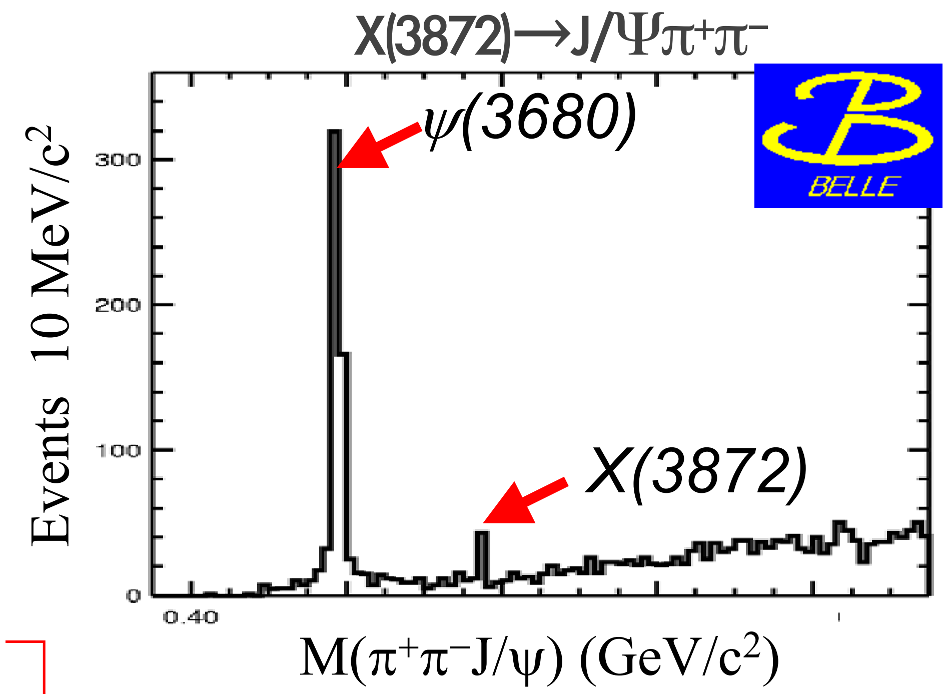


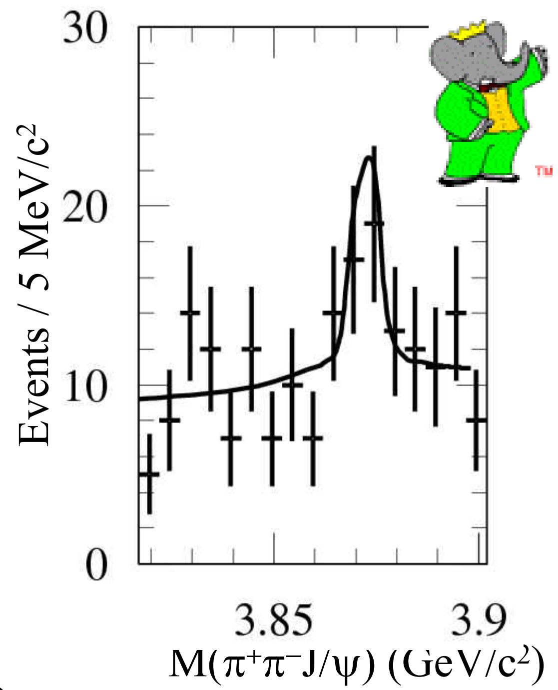

New particle X(3938), could be $\eta_c''$



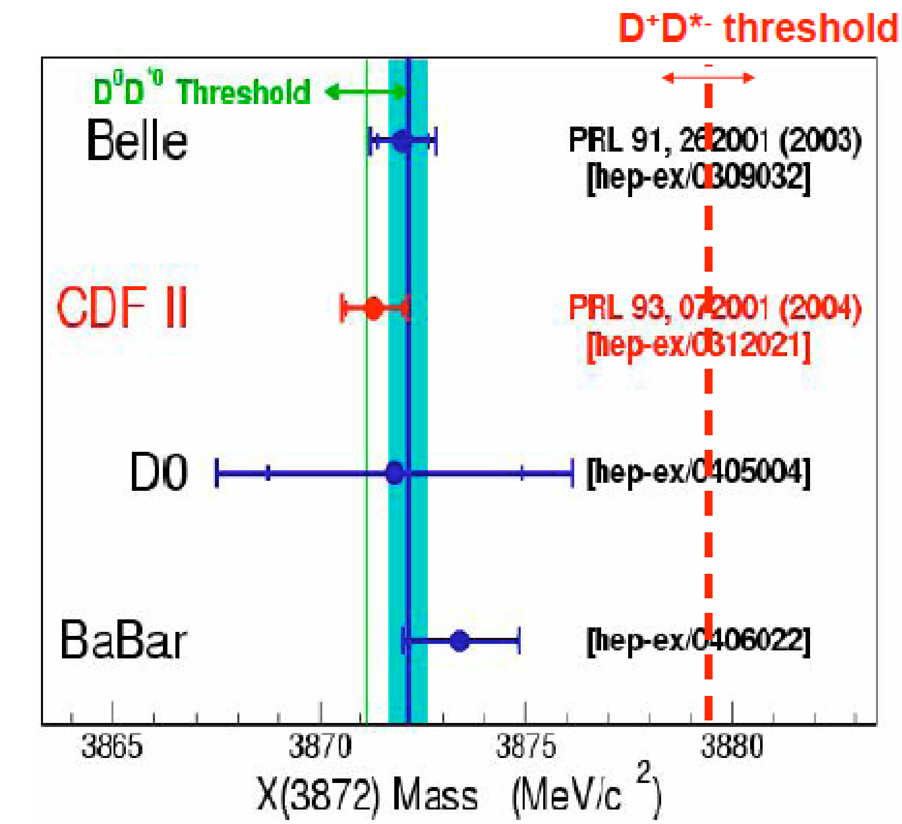

$J/\psi c\bar{c}$ results confirmed by BaBar

# New Heavy Particles




X(3872) Mass




X(3872) found in $B \to K(J/\Psi\pi^+\pi^-)$ (Belle) confirmed by CDF, D0, BaBar

⟨M⟩ $= 3871.9 \pm 0.6$ MeV , $\Gamma < 2.3$ MeV (90% C.L)

$D^0\bar{D}^{0*}$ threshold: $3871.3 \pm 1.0$ MeV

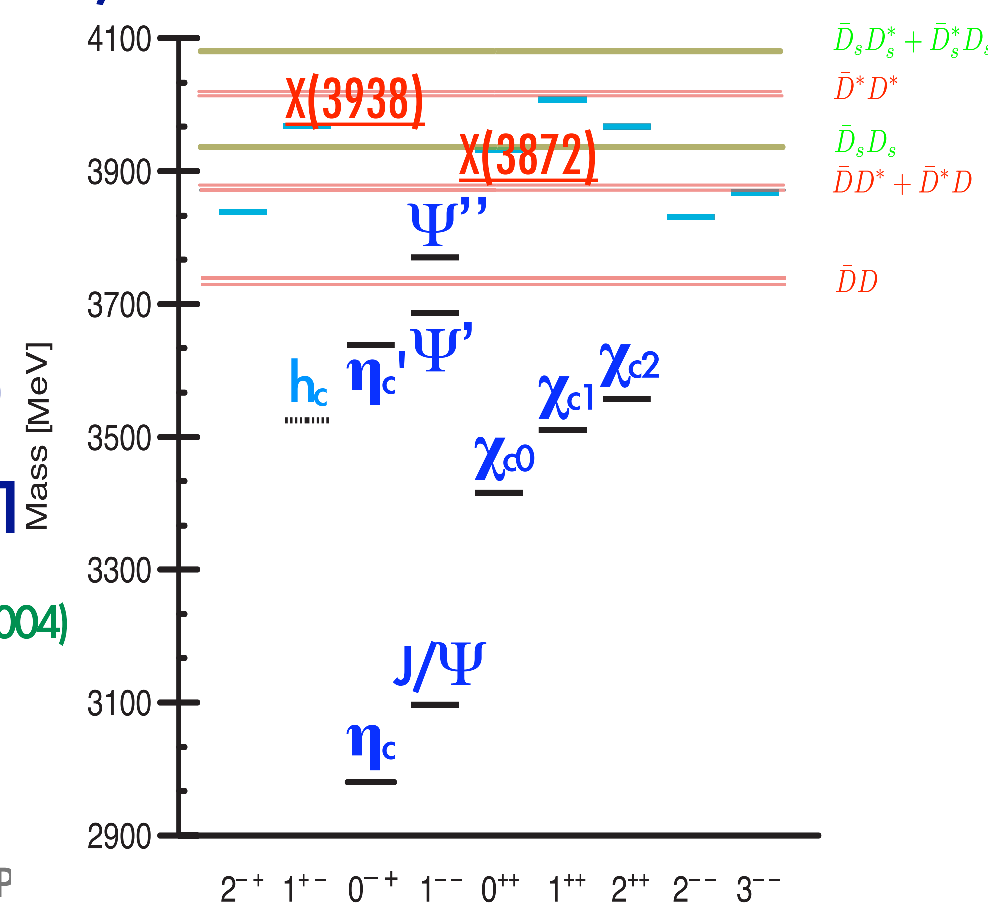
Favored $J^{PC} = 1^{++}$ (BELLE)

Analysis of angular and $\pi^+\pi^-$ dists. ($\pi^+\pi^-$ likely from $\rho^0$)

Decays $X \to J/\Psi\omega$ and $X \to J/\Psi\gamma$ seen, indicating C=+1

all consistent with a $D^0\bar{D}^{0*}$ molecule (!) E.S.Swanson PLB588,189(2004)

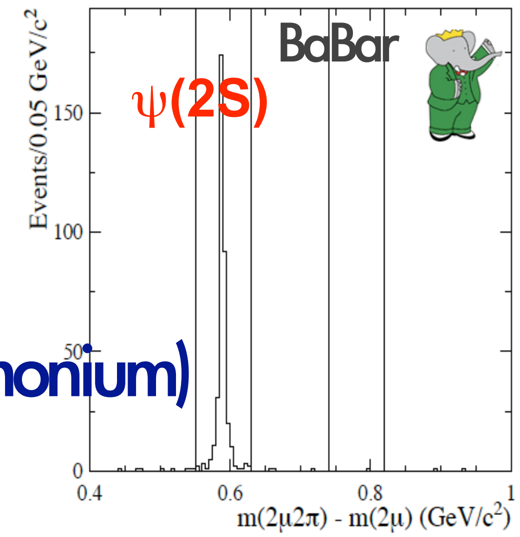
possibly with $J/\Psi\ \rho^0$ and $J/\Psi\omega$ admixture

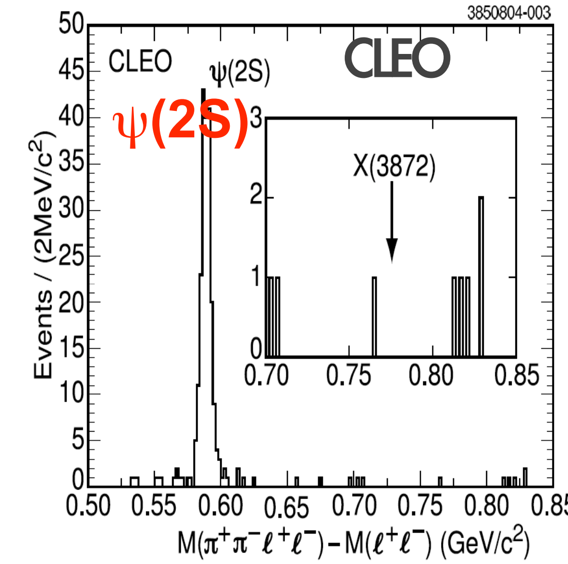


# New Heavy Particles

X(3872) in $\gamma\gamma$ and ISR ($e^+e^- \rightarrow \gamma_{ISR}\, J/\Psi\, \pi^+\pi^-$) ?

No signal found (would be expected for $1^{--}$ charmonium)



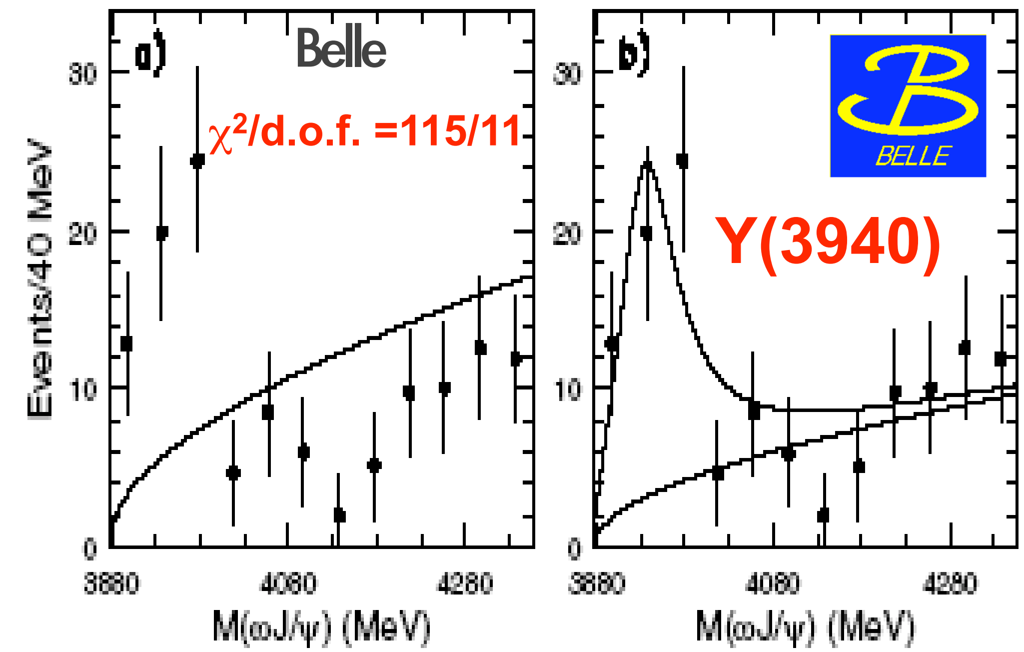




'By-products' of the X(3872) scrutiny:

Y(3940) found in $B \rightarrow K(J/\Psi\omega)$ decays (Belle)

above $D\bar{D}^*$ threshold, but no $D\bar{D}^*$ decays seen

Y(3940) a cc-g hybrid? But $M_{Lattice} \approx 4.4$GeV



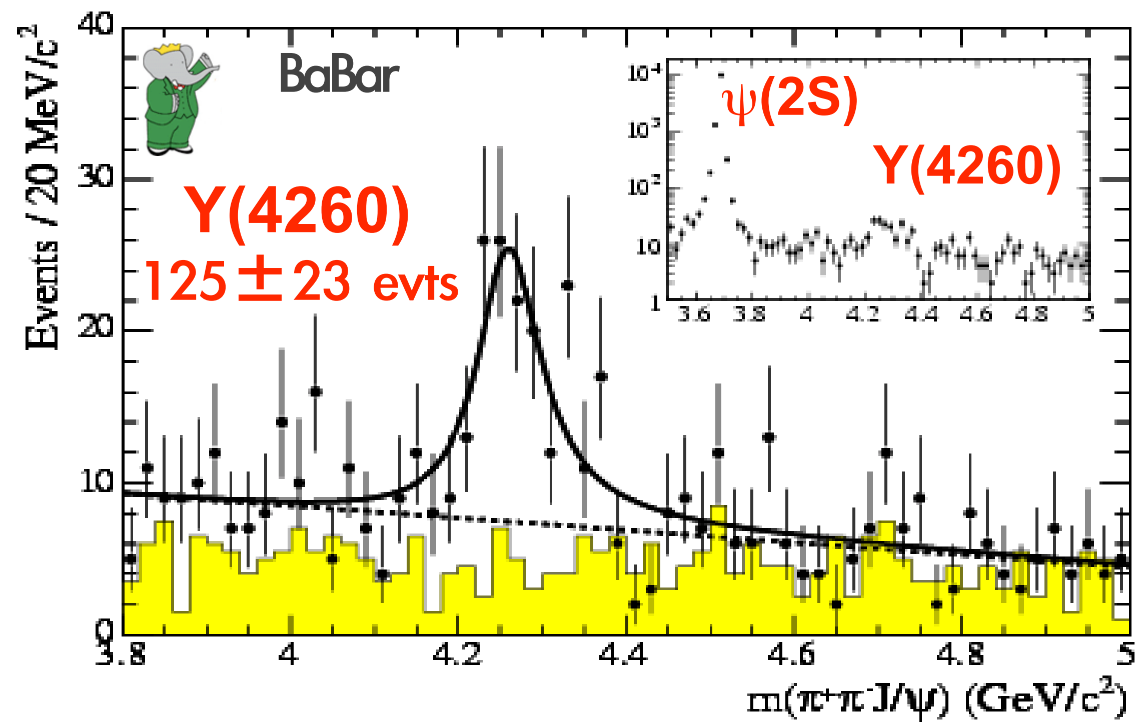

X(3938) (seen in $J/\Psi X$ recoil mass spectrum)

decays into $D\bar{D}^*$ seen, but no evidence for

decays into $J/\Psi\omega$, X(3938) could be the $\eta_c$''

Y(4260) found in $e^+e^- \rightarrow \gamma_{ISR}\, J/\Psi\, \pi^+\pi^-$

continuum scan (BaBar)




X(3872), X(3938), Y(3940), Y(4260), ...

opening up new fields of QCD

More data, more surprises !!!

# Conclusions

- Heavy Quark Production is a rich field of research
- sophisticated measurements with increasingly large data samples & vivid theoretical developments
- Charm Production: All about precision !
    - Proton structure: Precision ep data starting to constrain pQCD
    - Photon structure: Charm and beauty contributions to photon being explored
- Beauty Production: Many new measurements !
    - Theory improvements leading to converging picture (fragmentation, hadronisation)
    - High cross sections at LEP still unexplained
- Quarkonia: Still causing some trouble
    - Production process (rates and distributions) not quantitatively understood
    - NRQCD (LO) appears to be being disproved, (tedious) NLO calculations underway
- New Resonances:
    - Large statistics give access to new frontiers in the understanding of QCD
    - Quantum numbers being studied
    - Possibly new production mechanisms to be explained

More data, more surprises: Expect many new insights still at HERA, Tevatron & b-factories