p+p RHIC and lower energy highlights on quarkonium cross-section, polarization and SSA

Barbara Trzeciak
Utrecht University

New observables in quarkonium production
Trento, 29 Feb 2016 to 04 Mar 2015

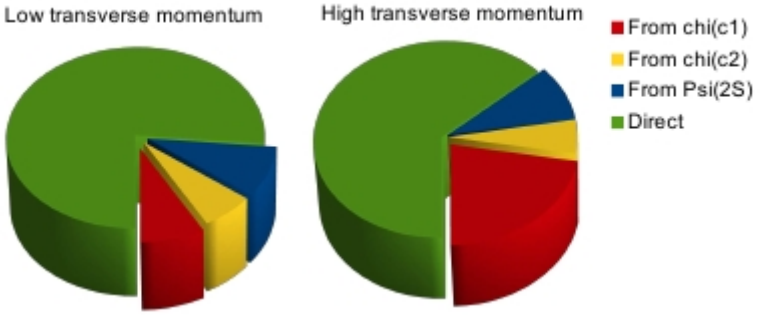
Feed-down to inclusive J/ψ production

- At these energies cross section and polarization measurements are mostly for inclusive J/ψ and ϒ production
  - → Feed-down from the excited states complicates the story

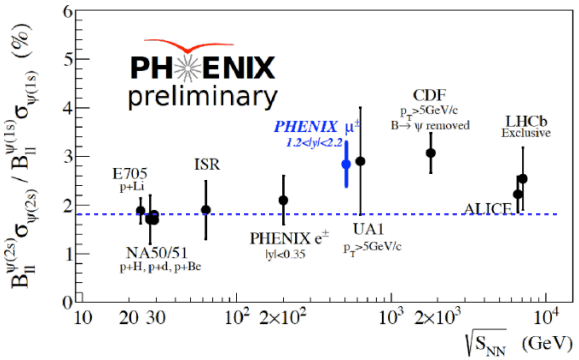
Feed-down to inclusive J/ψ production

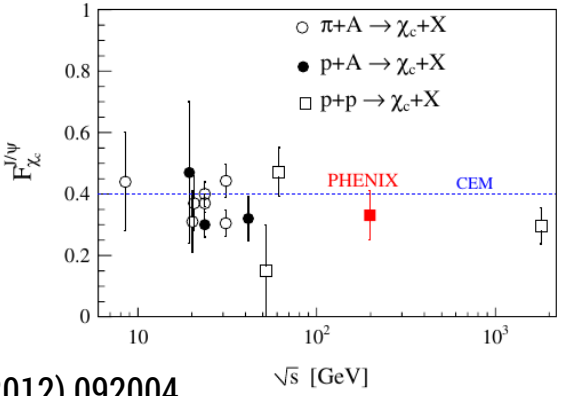
- At these energies cross section and polarization measurements are mostly for inclusive J/ψ production
  - Feed-down from the excited states and B complicates the story
    - ψ(2S) ~ 10% *no significant √s dependence observed;*
    - χ_c ~ 30%

Sources of prompt J/ψ



RHIC results: consistent with previous measurements at lower energies (and pA)





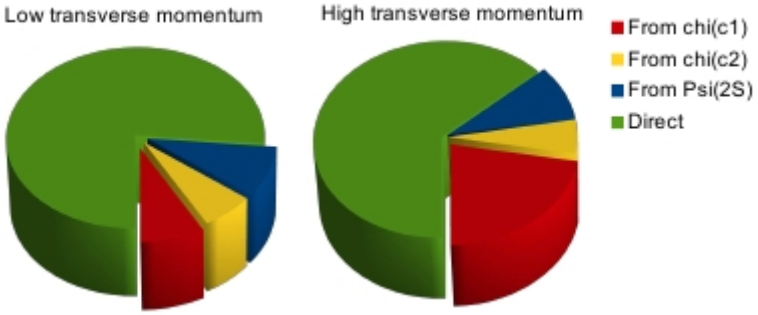
PRD 85 (2012) 092004
PHENIX Preliminary

Feed-down to inclusive J/ψ production

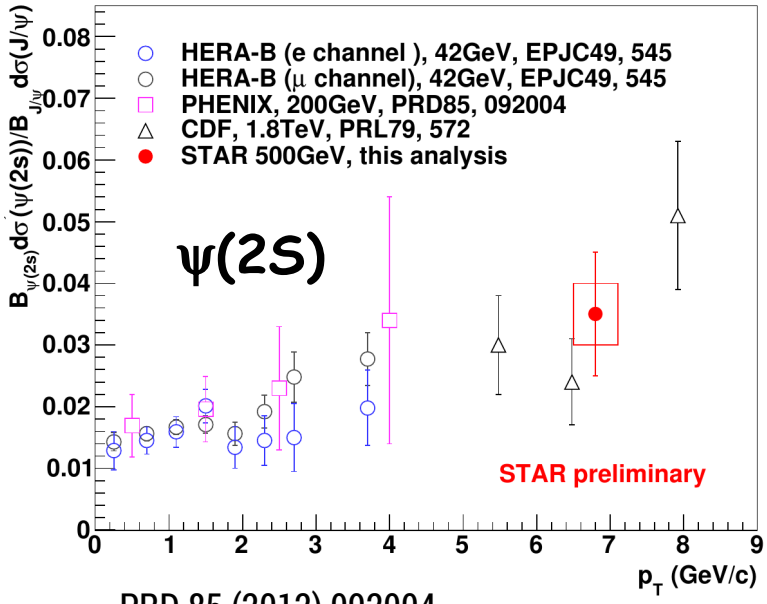
- At these energies cross section and polarization measurements are mostly for inclusive J/ψ production
  - Feed-down from the excited states and B complicates the story
    - ψ(2S) ~ 10%
    - χ_c ~ 30%

no significant √s dependence observed; however, the feed-down contribution increases with p_T

Sources of prompt J/ψ



RHIC results: consistent with previous measurements at lower energies (and pA)



PRD 85 (2012) 092004,
STAR preliminary

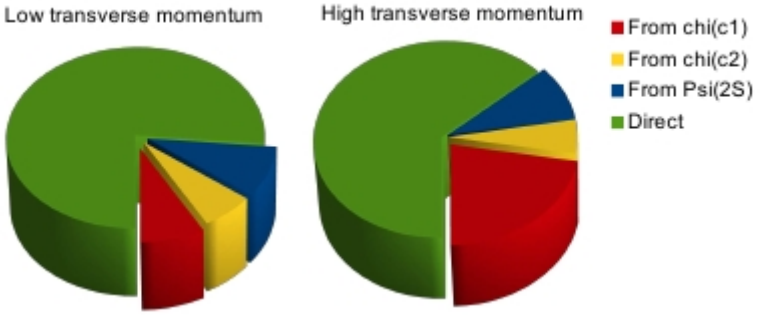
Feed-down to inclusive J/ψ production

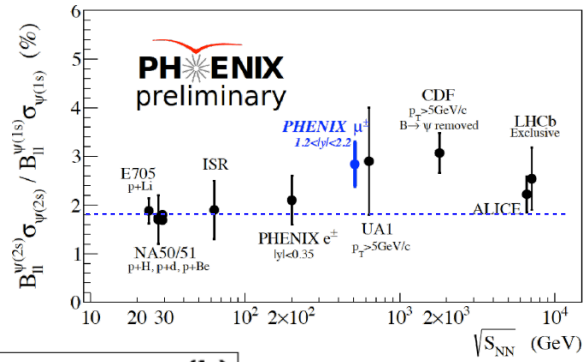
- At these energies cross section and polarization measurements are mostly for inclusive J/ψ production
  - Feed-down from the excited states and B complicates the story
    - ψ(2S) ~ 10%
    - χ_c ~ 30%

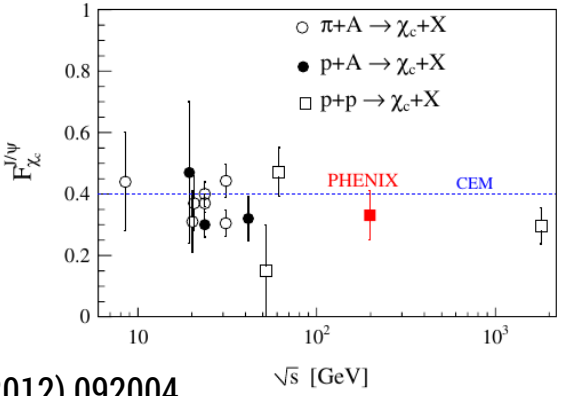
no significant √s dependence observed; however, the feed-down contribution increases with p_T

RHIC results: consistent with previous measurements at lower energies (and pA)

Sources of prompt J/ψ

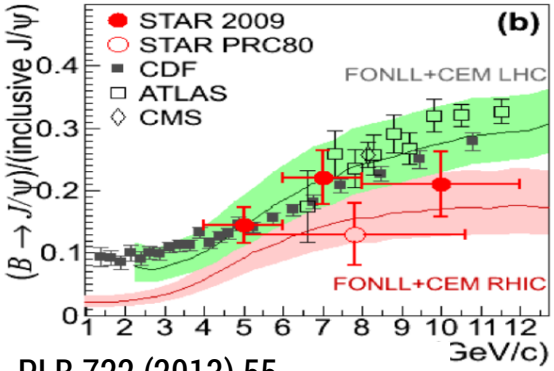






PRD 85 (2012) 092004
PHENIX Preliminary

- B → J/ψ:



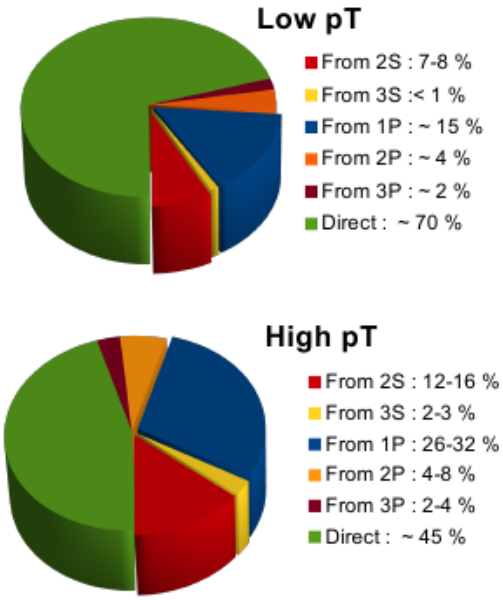
PLB 722 (2013) 55

Feed-down to inclusive Υ production

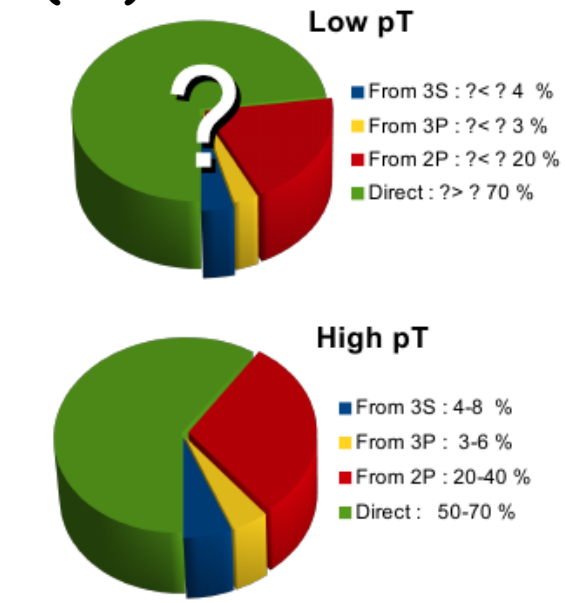
- At these energies cross section and polarization measurements are mostly for inclusive Υ production
  - Feed-down from the excited states complicates the story

Sources of:

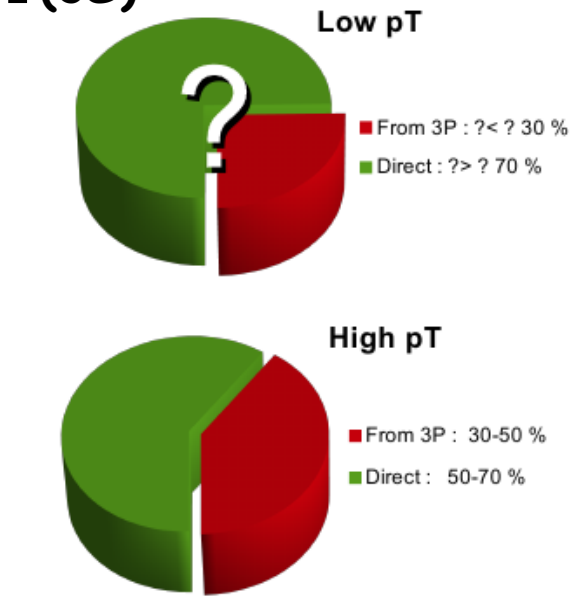
Υ(1S)



Υ(2S)



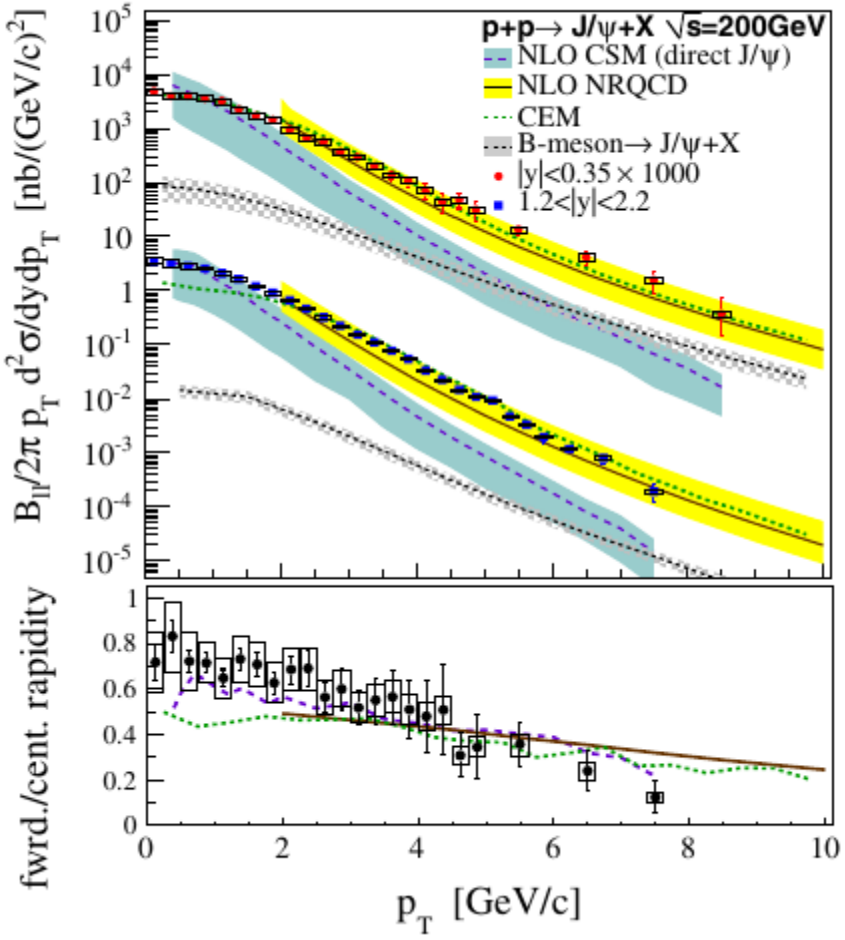
Υ(3S)



based mostly on LHC measurements

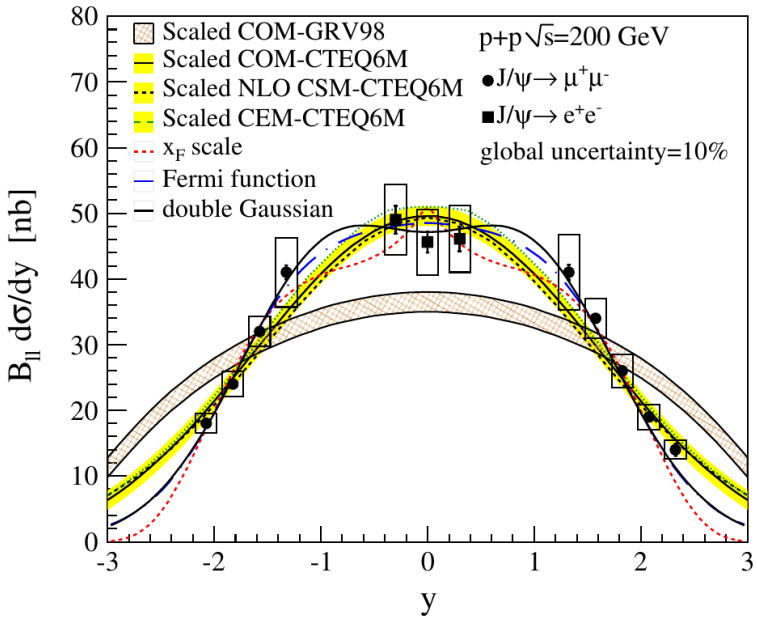
p_T and y differential J/ψ cross-sections RHIC

- p_T spectra at mid and forward rapidities @ $\sqrt{s}$ =200 GeV



System	$\langle p_T^2 \rangle$	$\langle p_T^2 \rangle\|_{p_T<5\ \mathrm{GeV/c}}$
J/ψ $1.2 < \|y\| < 2.2$	$3.63 \pm 0.03 \pm 0.09$	$3.43 \pm 0.02 \pm 0.08$
J/ψ $\|y\| < 0.35$	$4.41 \pm 0.14 \pm 0.18$	$3.89 \pm 0.11 \pm 0.15$
ψ' $\|y\| < 0.35$	$4.7^{+1.5}_{-1.05} \pm 0.4$	$4.7^{+1.5}_{-1.05} \pm 0.4$

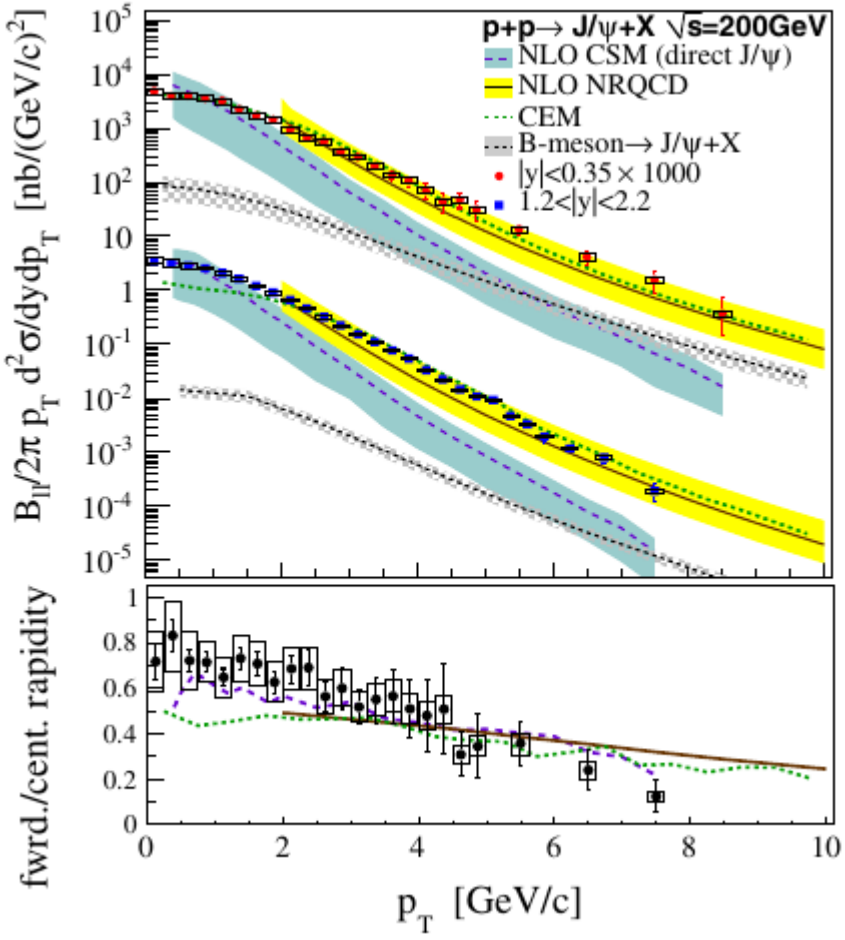
- *J/ψ p_T spectrum is harder at midrapidity*
- *models predict a downward trend, but the CEM and NRQCD do not follow the data slope*
- *the rapidity dependence supports use of CTEQ6M*



PRD 85 (2012) 092004

J/ψ cross-section – model comparison RHIC

- p_T spectra at mid and forward rapidities @ $\sqrt{s}$ =200 GeV

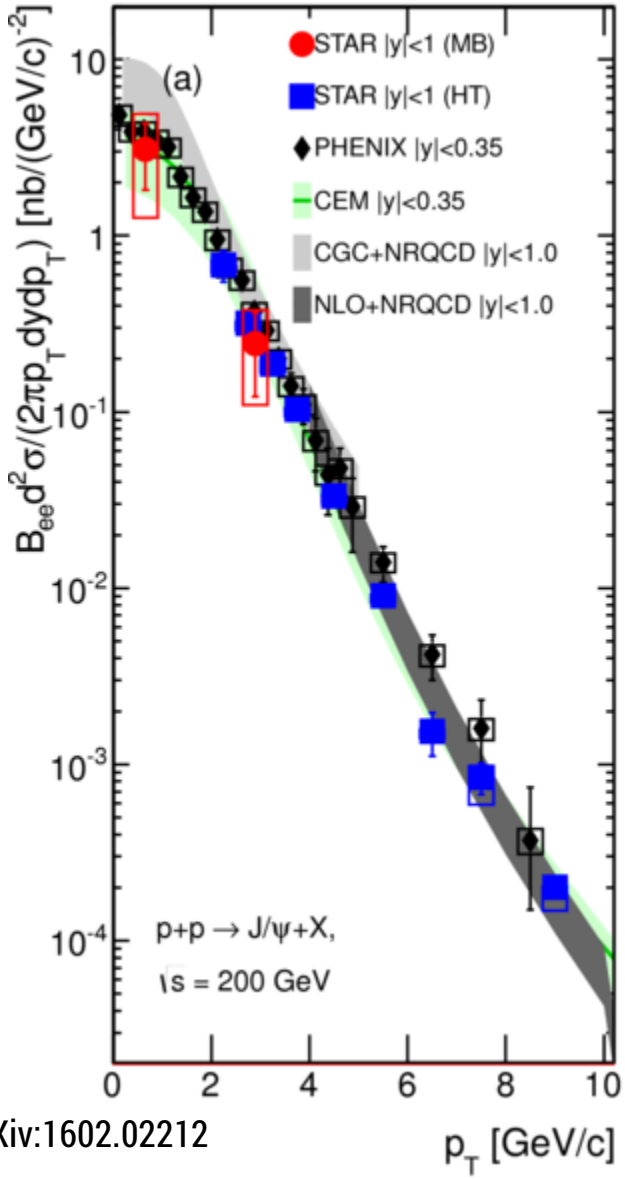


- *CEM and NRQCD (p_T > 2 GeV/c) provide good description*
- *(N)NLO CSM underpredicts the data and disagrees in the slope*

PRD 85 (2012) 092004

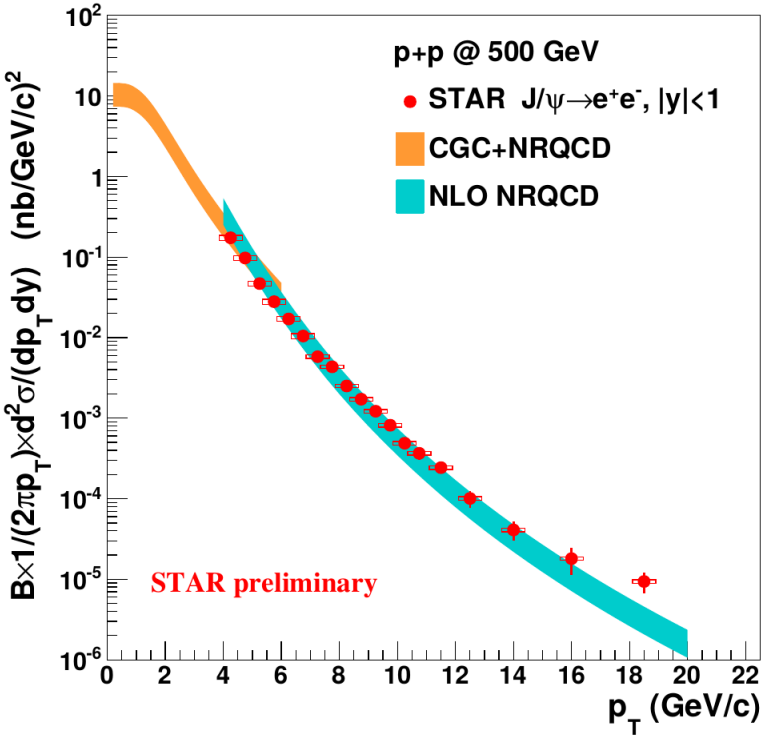
J/ψ cross-section – model comparison RHIC

- p_T spectra at midrapidity @ $\sqrt{s}$ =200 and 500 GeV

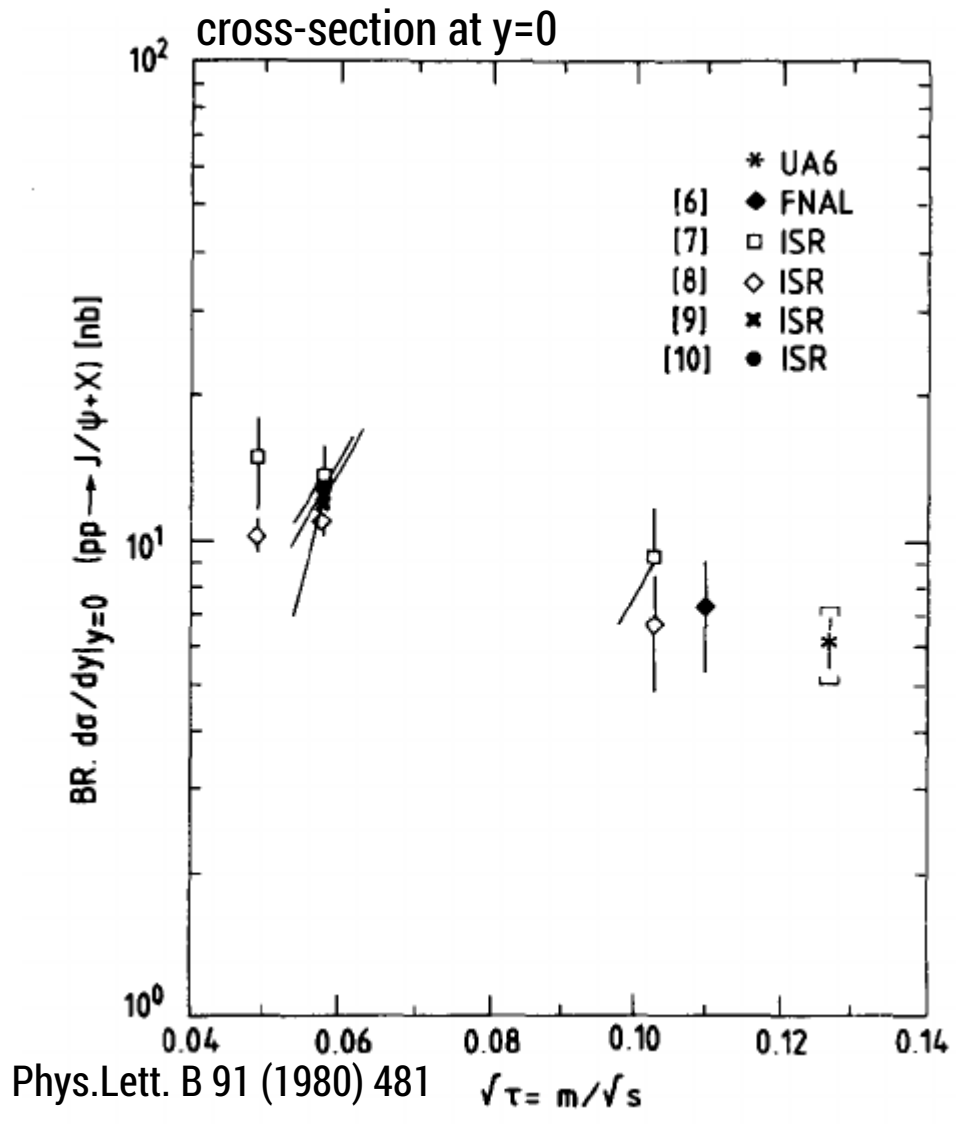


arXiv:1602.02212

- *CEM and NRQCD (p_T > 2 GeV/c) provide good description*
- *(N)NLO CSM underpredicts the data and disagrees in the slope*
- *CGC + NRQCD prediction for lower p_T range: agrees relatively well with the data*



J/ψ cross-section *vs* √s
Including results at lower energies



Phys.Lett. B 91 (1980) 481

J/ψ production at y=0

√s [GeV]	*experiment*
24.3	UA6
52.4, 53, 62.5, 63	ISR
200	PHENIX, STAR

J/ψ p_T differential cross-section

52,63	ISR
200	PHENIX, STAR
500	STAR (> 4GeV/c)

- *p_T differential cross-sections described well by (CGC+)NRQCD calculations*
- *however more tension in describing p_T integrated yields and polarization*

arXiv: 1504.00317

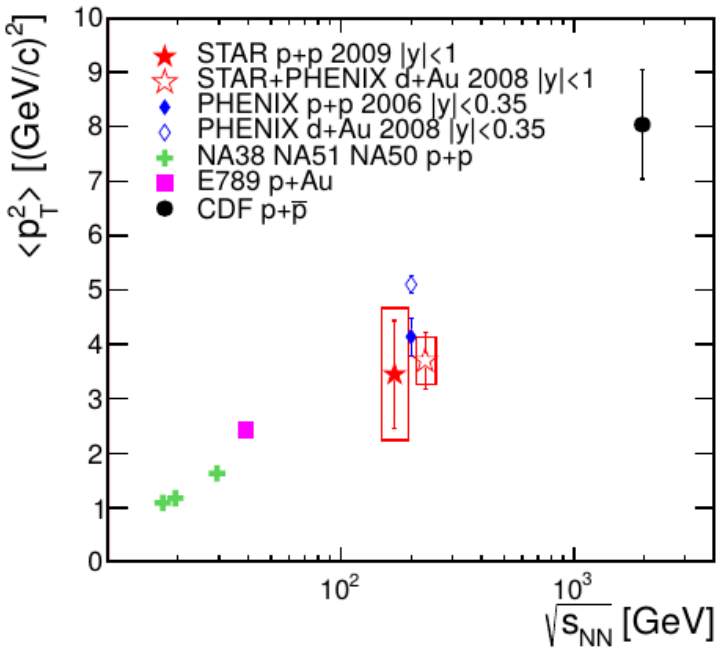
J/ψ $\langle p_T^2 \rangle$ *vs* $\sqrt{s}$ and x_T scaling

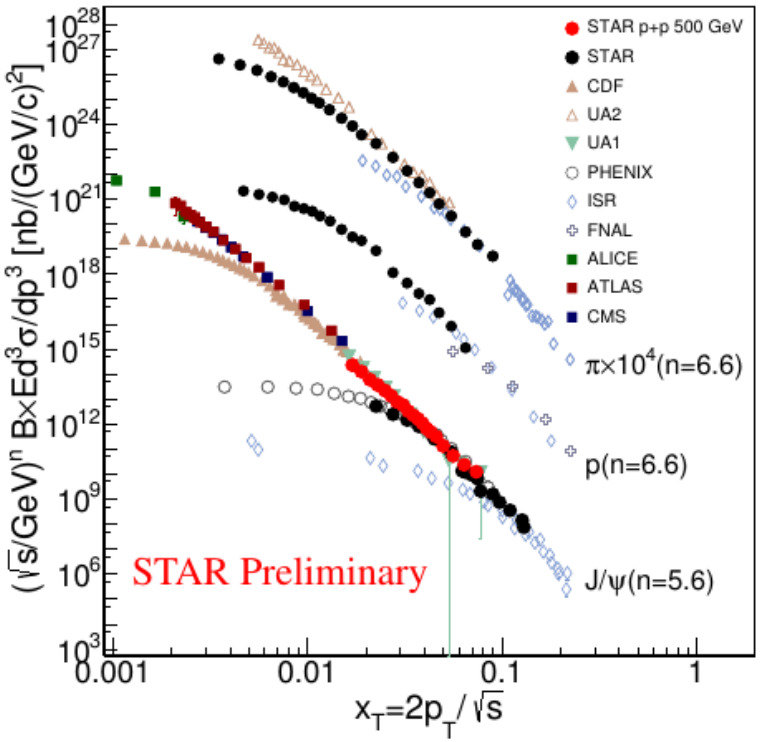
- $\langle p_T^2 \rangle$ *of inclusive J/ψ increases with* $\sqrt{s}$
- *the increase is ~linear with ln*$\sqrt{s}$ *at* $\sqrt{s}$ *= 17-200 GeV*
- *higher* $\langle p_T^2 \rangle$ *at mid than at forward rapidity (PHENIX@200GeV)*

- x_T *scaling of cross-section*

$$\frac{d^2\sigma}{2\pi\, p_T\, dp_T\, dy} = g(x_T)/(\sqrt{s})^n$$

for $x_T > 0.1$ *with n = 5.6, for all energies*





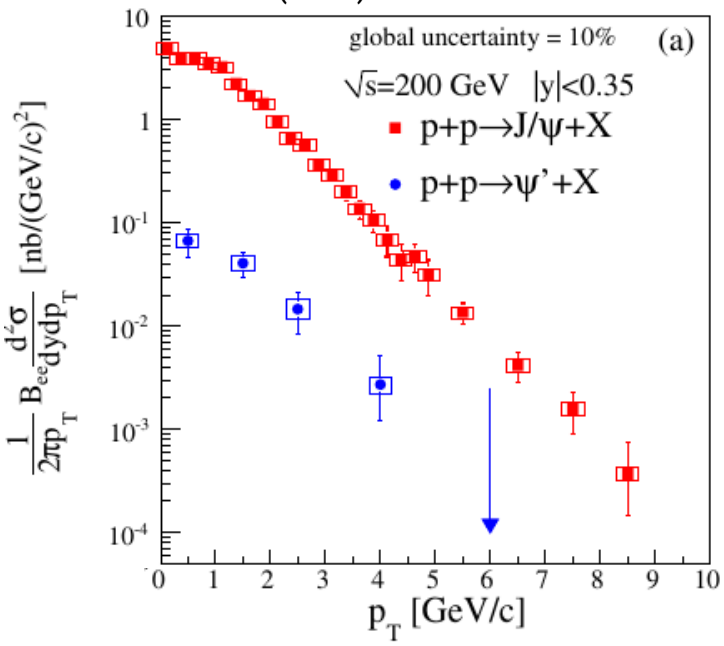
arXiv:1602.02212

ψ(2S) cross-section *vs* √s

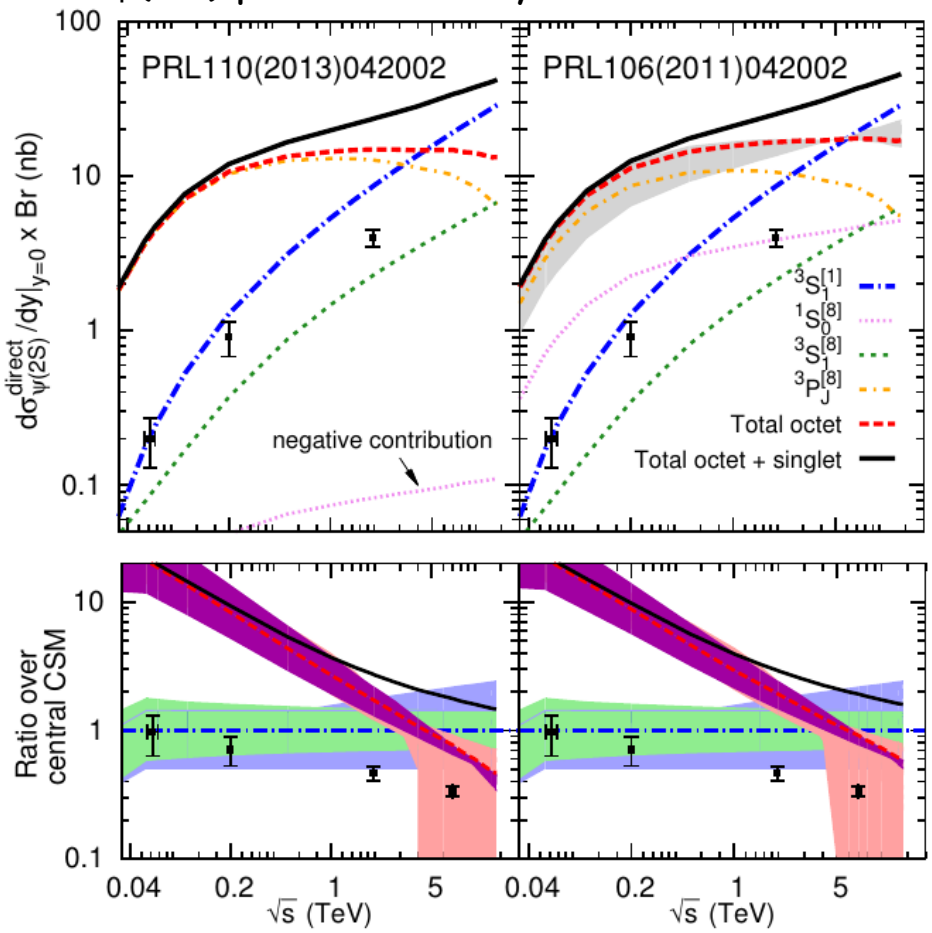
- cleaner probe, however not many measurements available

√s [GeV]	*experiment*
52.4 - 62.7	ISR
200	PHENIX

PRD 85 (2012) 092004



ψ(2S) production at y=0

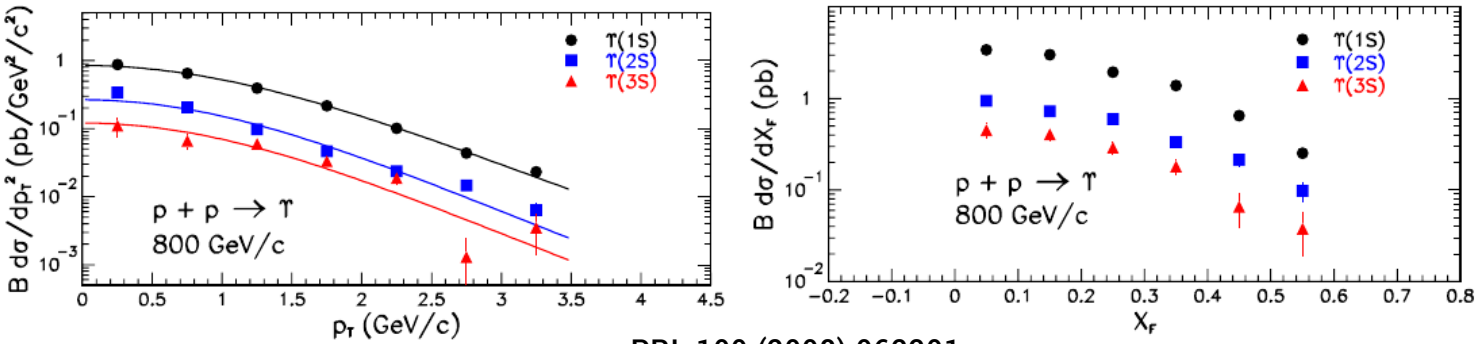


→ *NLO NRQCD overestimates p_T integrated yields*

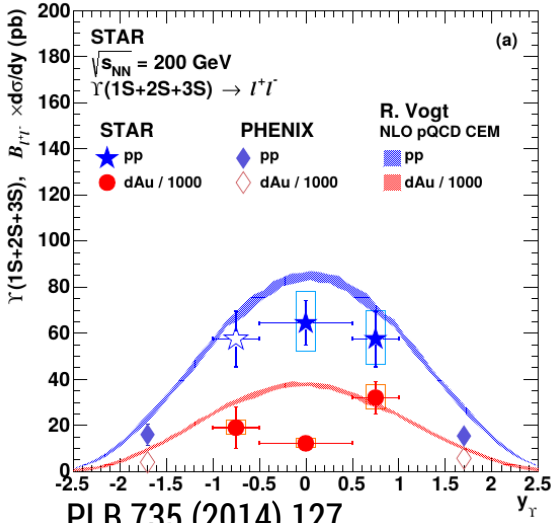
arXiv: 1504.00317

Υ cross-section *vs* √s

- Most measurements for Υ(1S+2S+3S)
  - E866/NuSea measured the Υ three states



PRL 100 (2008) 062301

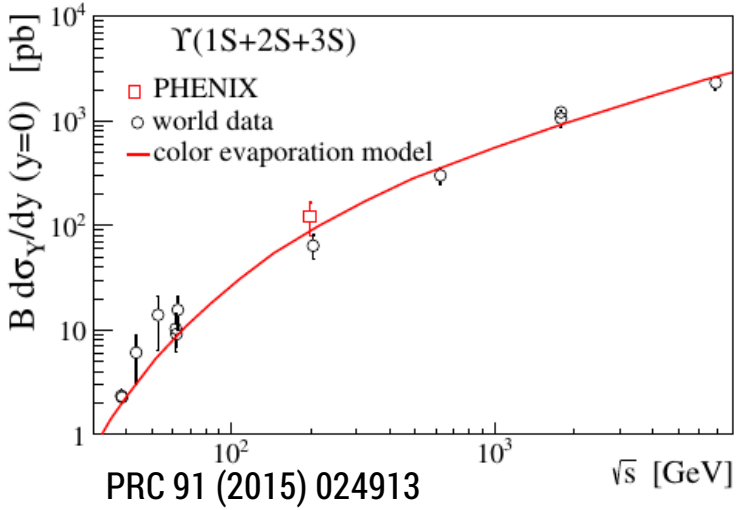


PLB 735 (2014) 127

- *Production and rapidity dependence described well by NLO CEM calculations*
- *NLO NRQCD for p_T integrated yields does much better job in the Υ case*

arXiv: 1504.00317

√s [GeV]	*experiment*
38	E866
52.4 - 62.7	ISR
200	STAR, PHENIX



PRC 91 (2015) 024913

J/ψ polarization

- *more constraints for the production mechanism models – smoking gun ?*
- results in pp and pA of inclusive J/ψ polarization

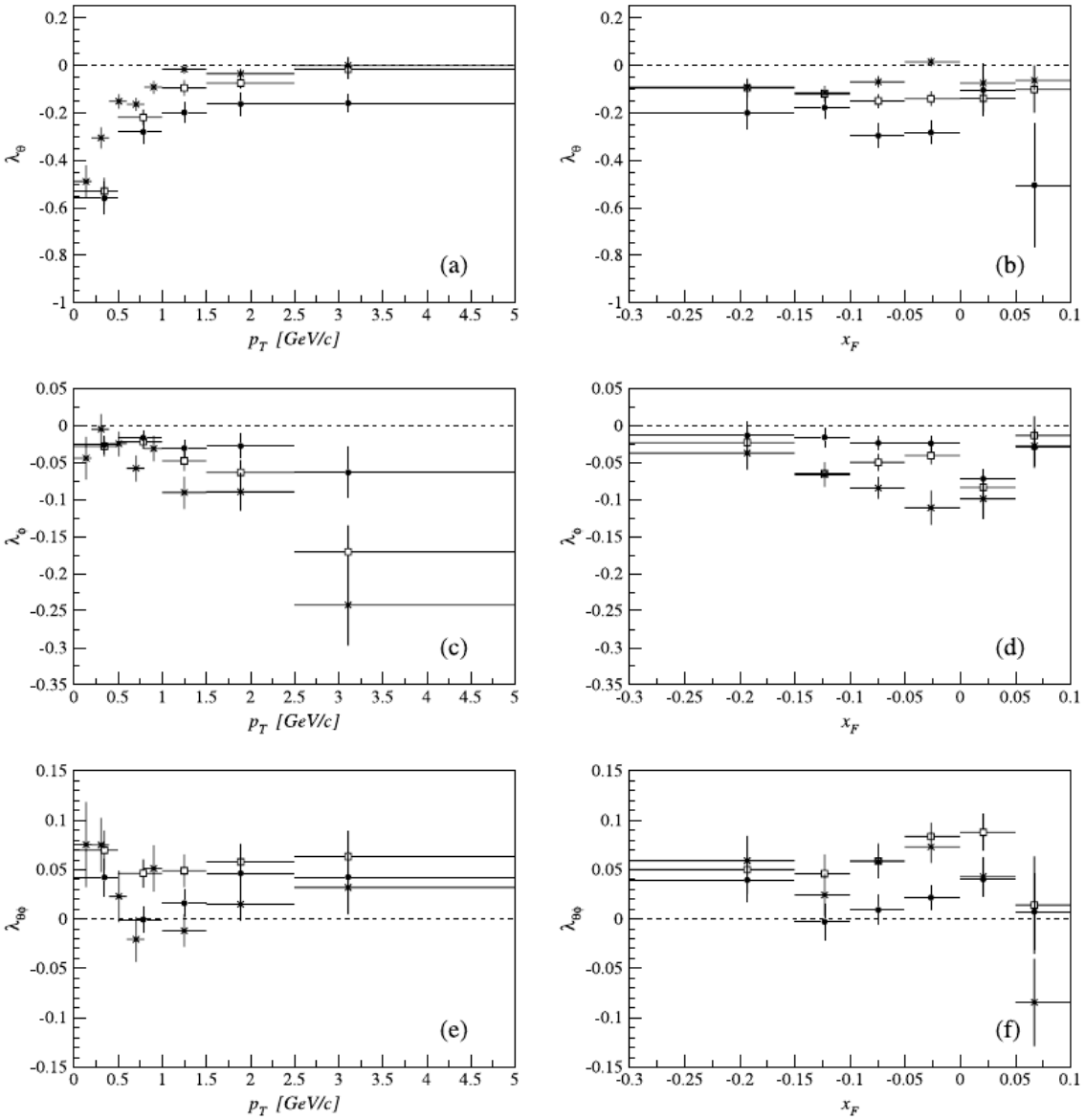
$\sqrt{s}$ GeV	colliding system	experiment	y range	p_T range [GeV/c]	measured parameters	Observed trend
200	pp	PHENIX	|y|<0.35	0-5	λ_θ vs p_T in HX & GJ	λ_θ values from slightly positive (consistent with 0) to negative as p_T increases
200	pp	STAR	|y|<1	2-6	λ_θ vs p_T in HX	λ_θ values from slightly positive (consistent with 0) to negative as p_T increases
500	pp	STAR	|y|<1	5-16	$\lambda_\theta, \lambda_\varphi$ & λ_{inv} vs p_T in HX & CS	λ_θ increase towards negative (positive) values in HX (CS) frame with increasing p_T; λ_φ consistent with 0 in HX, increasing with p_T in CS; λ_{inv} consistent in both frames
17.2	pA	NA60	0.28-0.78	----	$\lambda_\theta, \lambda_\varphi$ vs p_T in HX	$\lambda_\theta, \lambda_\varphi$ consistent with 0; slight increase of λ_θ with increasing p_T, no p_T dependence of λ_φ
27.4	pA	NA60	-0.17-0.33	----	$\lambda_\theta, \lambda_\varphi$ vs p_T in HX	$\lambda_\theta, \lambda_\varphi$ consistent with 0,
31.5	p-Be	E672/E702	x_F: 0.0-0.6	0-10	λ_θ in GJ	λ_θ= -0.01 ± 0.12 ± 0.09
38.8	p-Be	E672/E706	x_F: 0.0-0.6	0-10	λ_θ in GJ	λ_θ= -0.11 ± 0.12 ± 0.09
38.8	p-Si	E771	x_F: -005 – 0.25	0-3.5	λ_θ in GJ	λ_θ= -0.09 ± 0.12
38.8	p-Cu	E866/NuSea	x_F: 0.25-0.9	0-4	λ_θ vs p_T and x_F in CS	λ_θ values from small positive to negative with increasing x_F, no significant p_T dependence
41.6	p-C,W	HERA-B	x_F: -0.34-0.14	0-5.4	$\lambda_\theta, \lambda_\varphi, \lambda_{\theta\varphi}$ vs p_T and x_F in HX,CS, GJ	λ_θ and λ_φ<0, $\lambda_\theta(\lambda_\varphi)$ decrease (increase) with increasing p_T; no strong x_F dependence for p_T>1GeV/c; $\lambda_{\theta\varphi}$ depends on the frame; $\lambda_\theta^{CS} > \lambda_\theta^{HX} \approx 0$, $\lambda_\varphi^{HX} \neq 0$

J/ψ polarization at √s = 41.6 GeV

- *HERA-B measured all parameters in HX, CS and GJ frames*
  - *negative λ_θ at lower p_T in all frames*
  - $|\lambda_\theta(\mathrm{HX})| < |\lambda_\theta(\mathrm{GJ})| < |\lambda_\theta(\mathrm{CS})|,$

    $|\lambda_\phi(\mathrm{HX})| > |\lambda_\phi(\mathrm{GJ})| > |\lambda_\phi(\mathrm{CS})|,$

EPJ C 60 (2009) 517



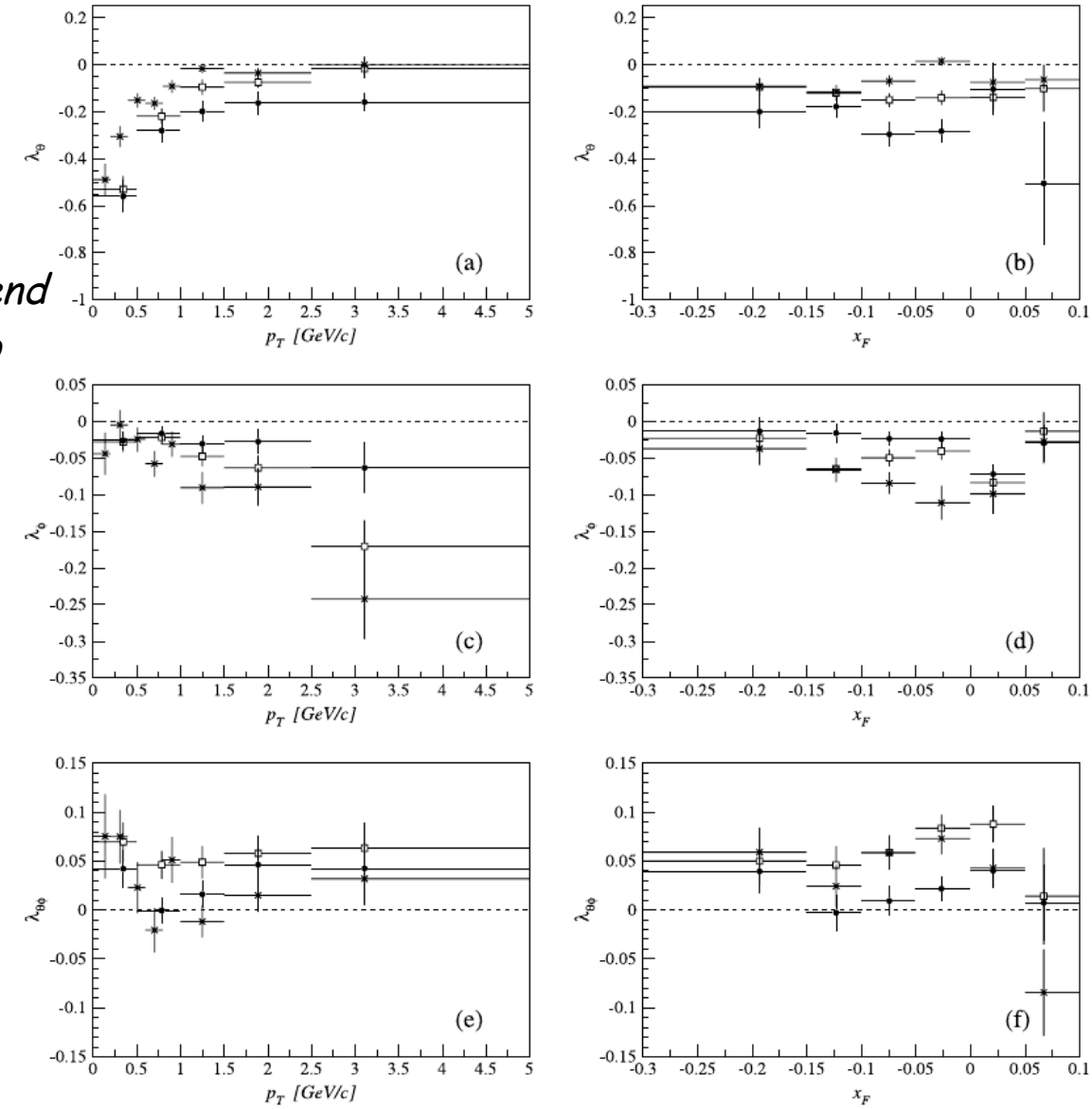
Nucl.Phys. A 830 (2009) 345

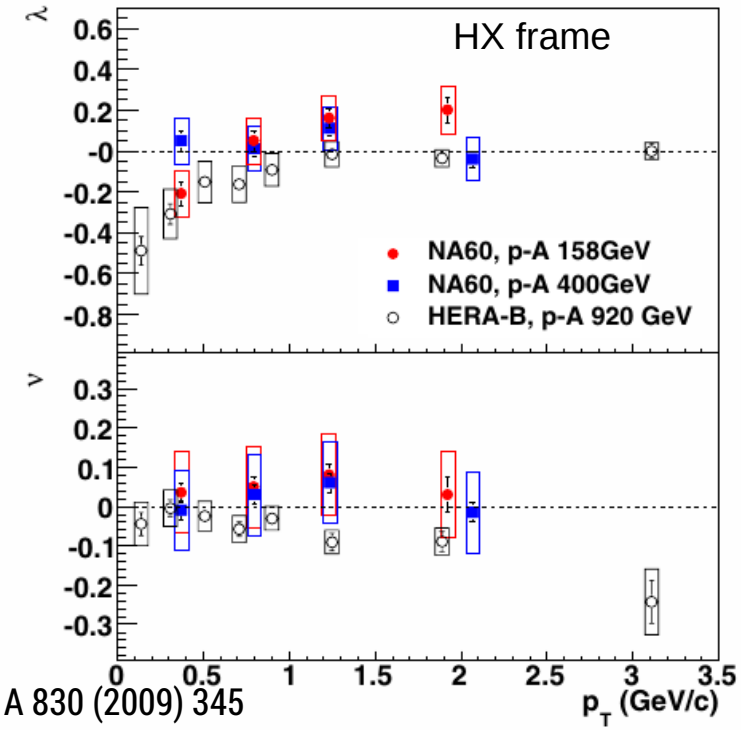
J/ψ polarization at √s ≤ 41.6 GeV

- *HERA-B measured all parameters in HX, CS and GJ frames*
  - *negative λ_θ at lower p_T in all frames*
  - $|\lambda_\theta(\mathrm{HX})| < |\lambda_\theta(\mathrm{GJ})| < |\lambda_\theta(\mathrm{CS})|,$

    $|\lambda_\phi(\mathrm{HX})| > |\lambda_\phi(\mathrm{GJ})| > |\lambda_\phi(\mathrm{CS})|,$
- *NA 60 results at 27.4 GeV confirm the trend*
- *experiments at lower energies observed no significant polarization*

EPJ C 60 (2009) 517

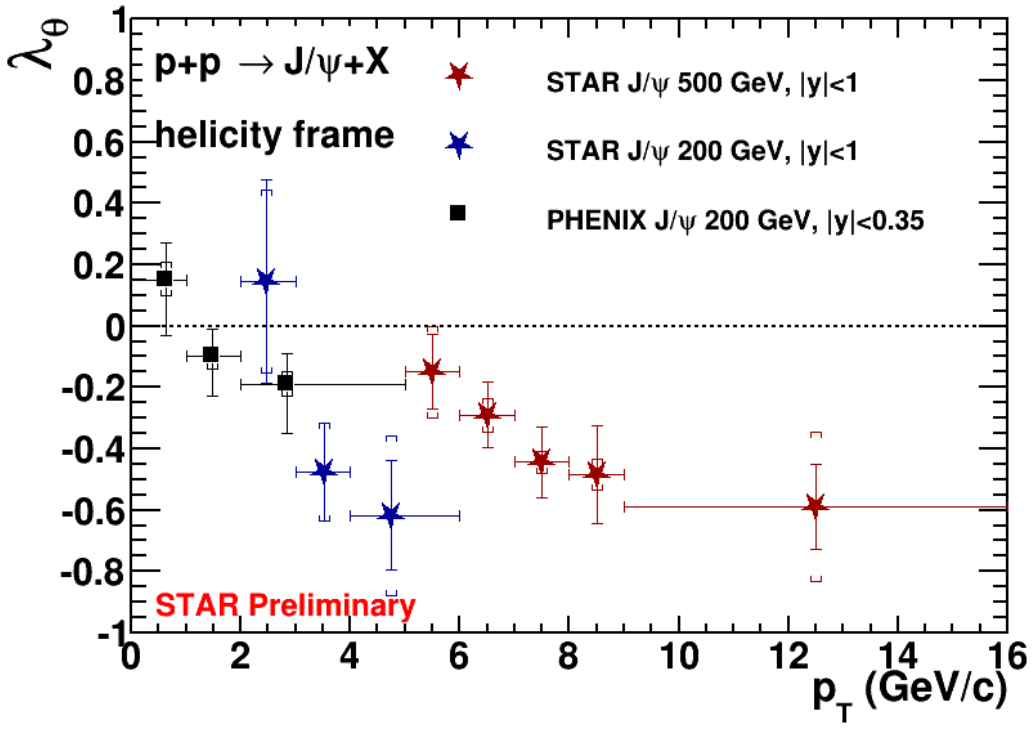




Nucl.Phys. A 830 (2009) 345

J/ψ polarization at √s = 200 and 500 GeV

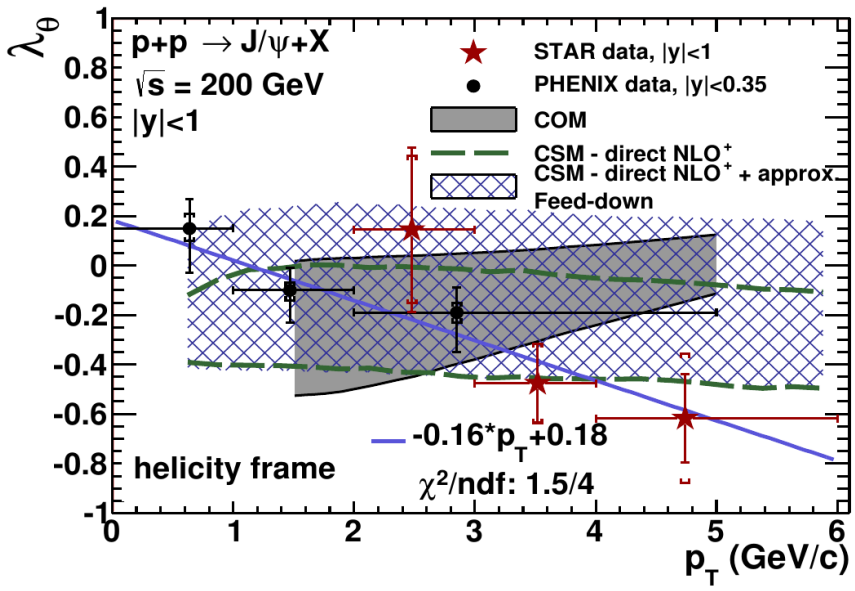
- λ_θ in the helicity frame
  - → *similar p_T trend at both energies, towards negative values of λ_θ*

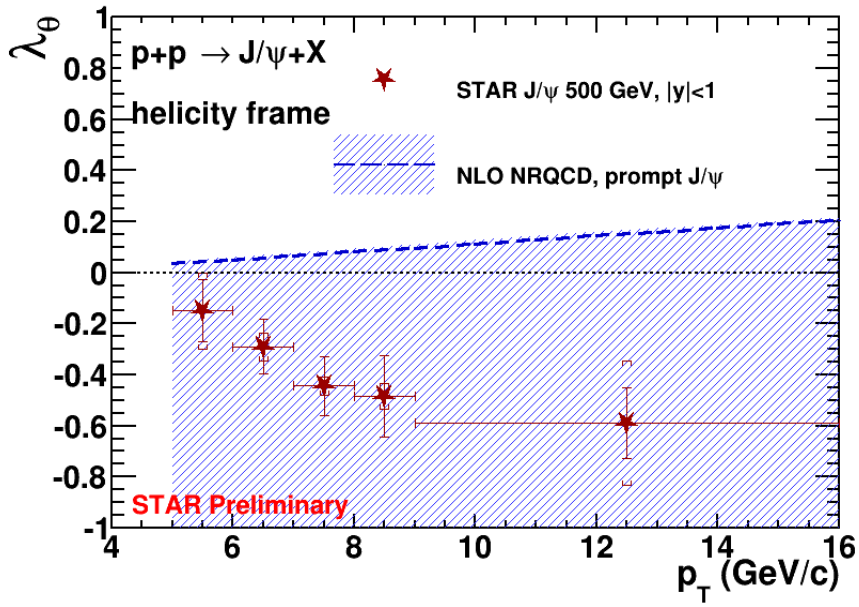


PLB 739 (2014) 180

J/ψ polarization at √s = 200 and 500 GeV

- λ_θ in the helicity frame
  - *similar p_T trend at both energies, towards negative values of λ_θ*
  - *200 GeV data consistent with NLO+ CSM prediction*
  - *data show different trend than NRQCD calculations*

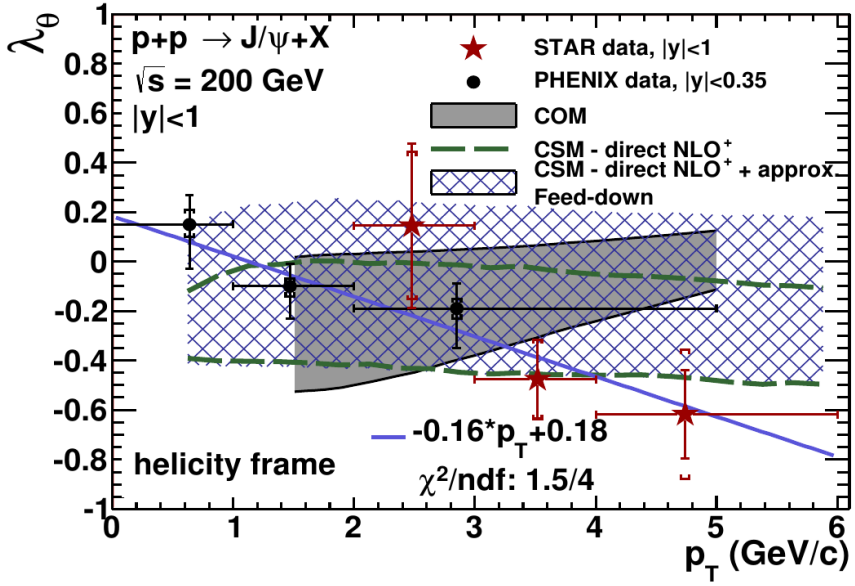


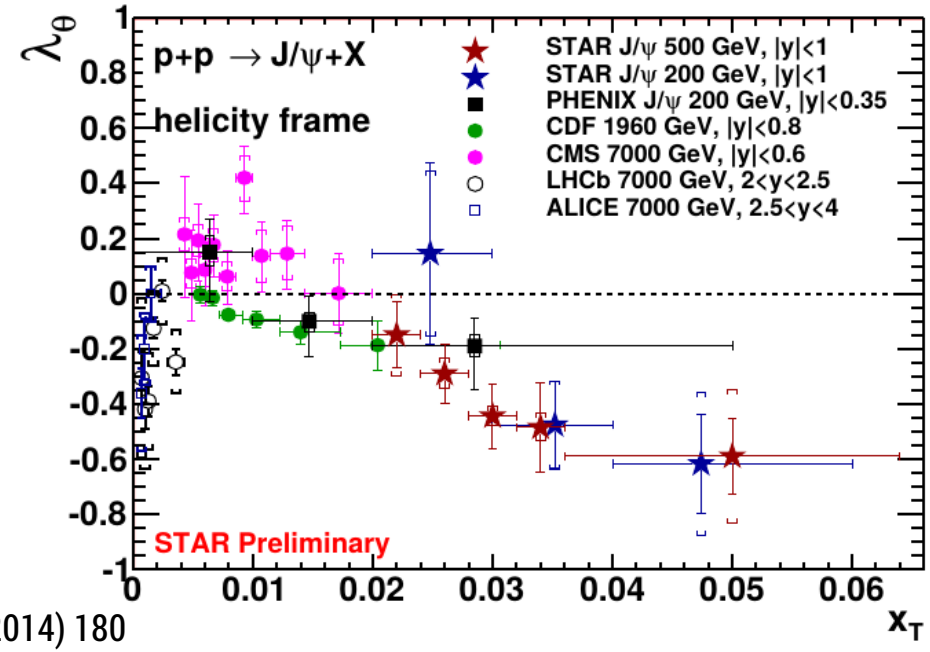


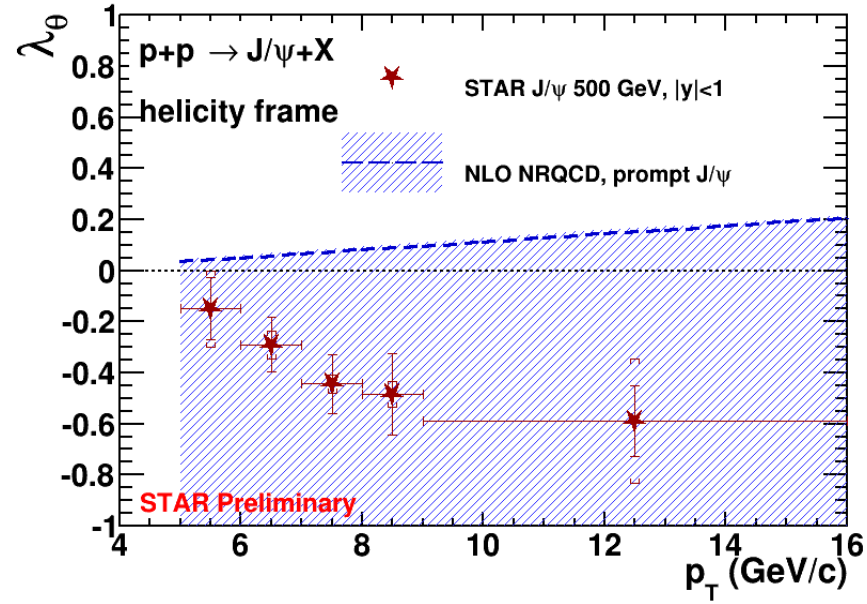
PLB 739 (2014) 180

J/ψ polarization at √s = 200 and 500 GeV

- λ_θ in the helicity frame
  - *similar p_T trend at both energies, towards negative values of λ_θ*
  - *200 GeV data consistent with NLO+ CSM prediction*
  - *data show different trend than NRQCD calculations*
  - *common x_T trend*





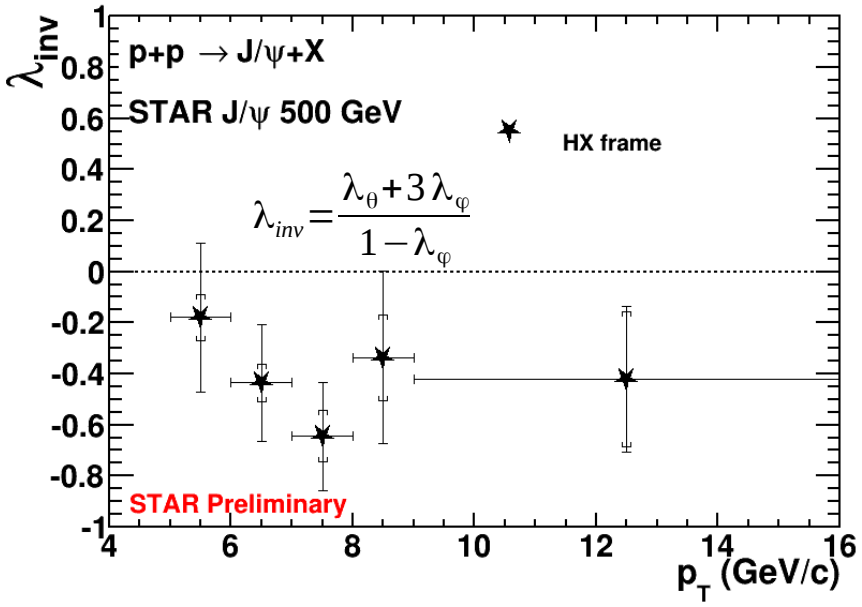


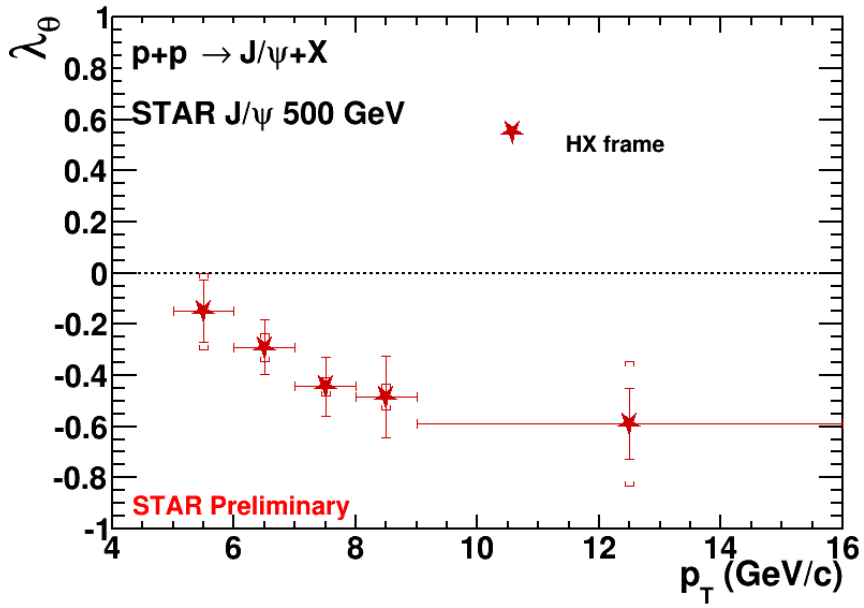
PLB 739 (2014) 180

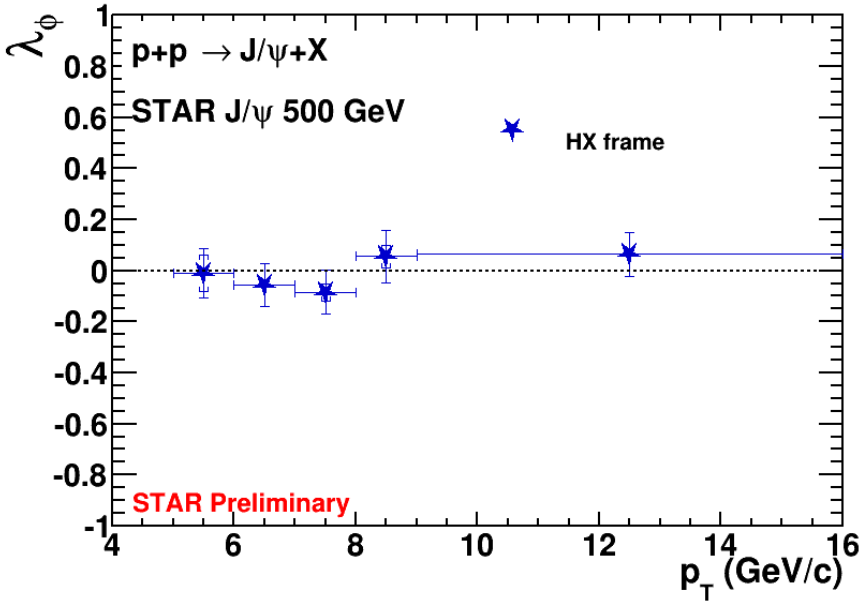
J/ψ polarization at √s = 500 GeV

- λ_θ, λ_φ and λ_{inv} and in the helicity frame

  - *no strong azimuthal anisotropy observed @ 500 GeV*
  - *negative values of* λ_{inv}



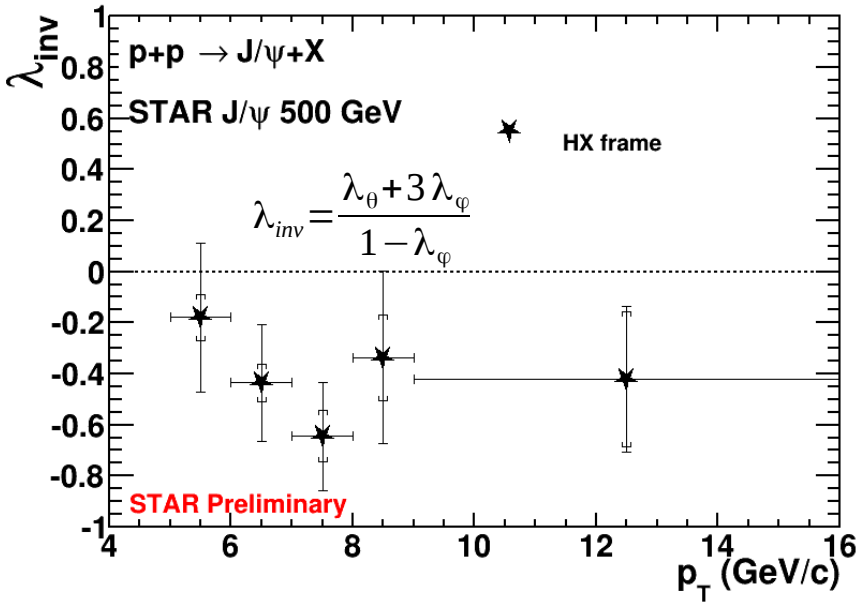


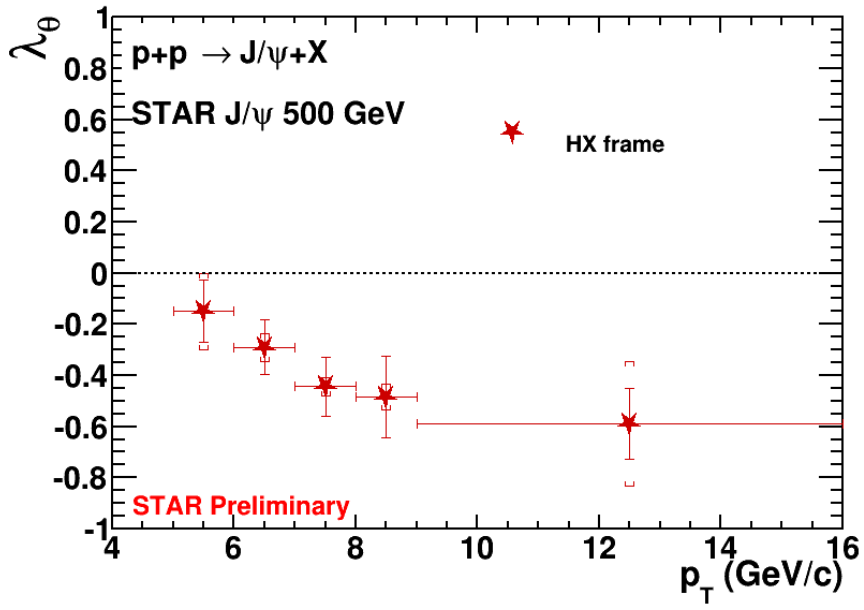


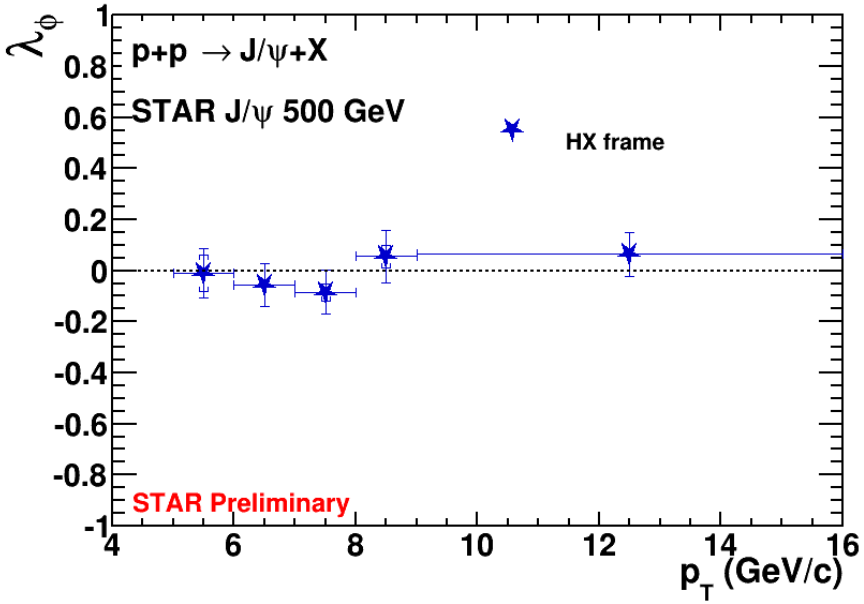
J/ψ polarization at √s = 500 GeV

- λ_θ, λ_φ and λ_{inv} and in the helicity frame

  - *no strong azimuthal anisotropy observed @ 500 GeV*
  - *negative values of* λ_{inv}

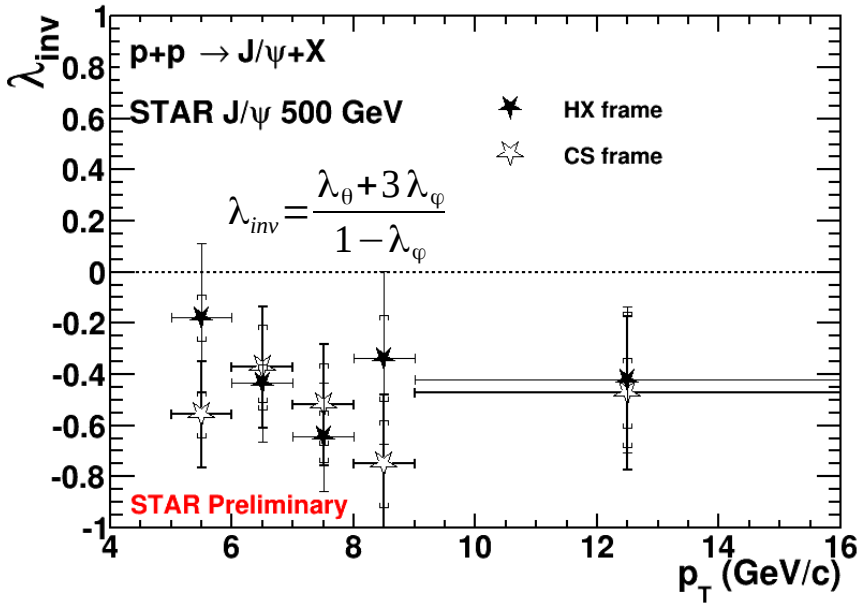


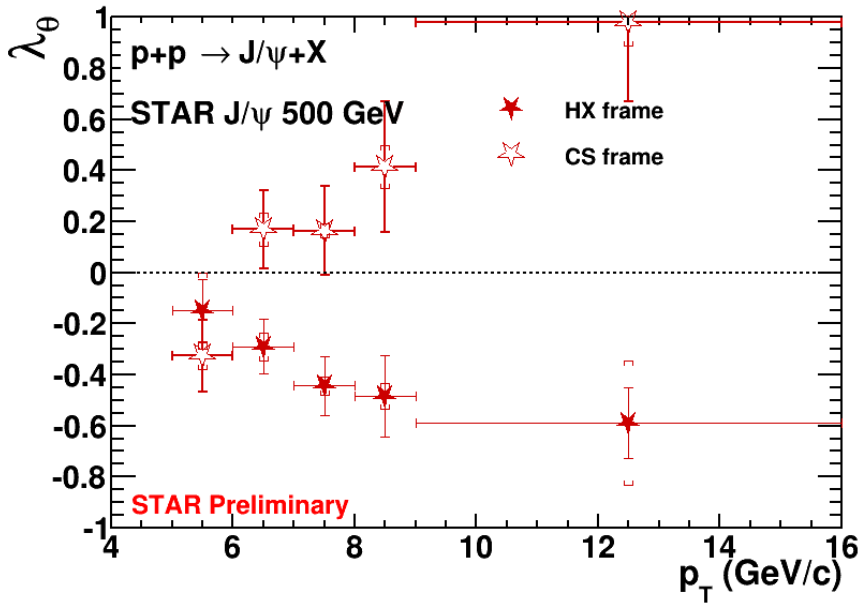


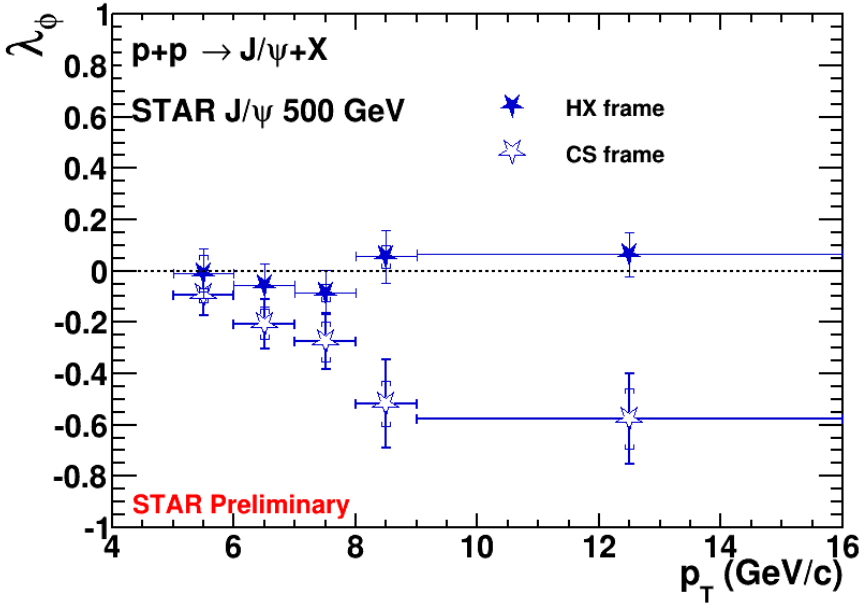


J/ψ polarization at √s = 500 GeV

- λ_θ, λ_φ and λ_{inv} and in the HX and CS frames
  - λ_{inv} *vs* p_T consistent between both frames
  - trend towards longitudinal polarization







J/ψ transverse SSA

- *provide an access to gluon dynamics within the nucleon*
- *can be sensitive to the the J/ψ production mechanism if the gluon Sivers function is nonzero:*
  - *finite transverse SSA for the color-singlet production* PLB 102 (1981) 364
  - *vanishes in the case of the color-octet* PRD 51 (1995) 1125, PRD 55 (1997) 5853

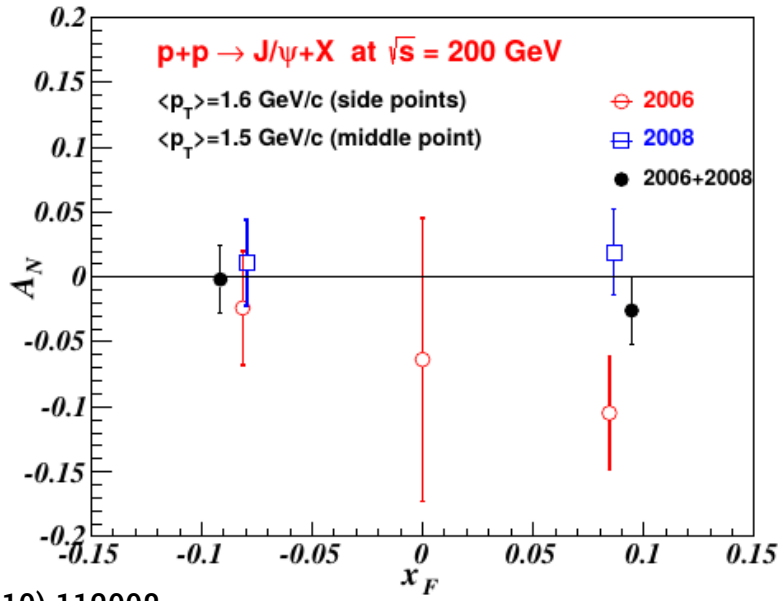
- PHENIX measured J/ψ production from transversely polarized p+p collisions at 200 GeV at $|y| < 0.35$ and $1.2 < |y| < 2.2$ for $p_T < 6$ GeV/c PRD 82 (2010) 112008 PRD 86 (2012) 099904

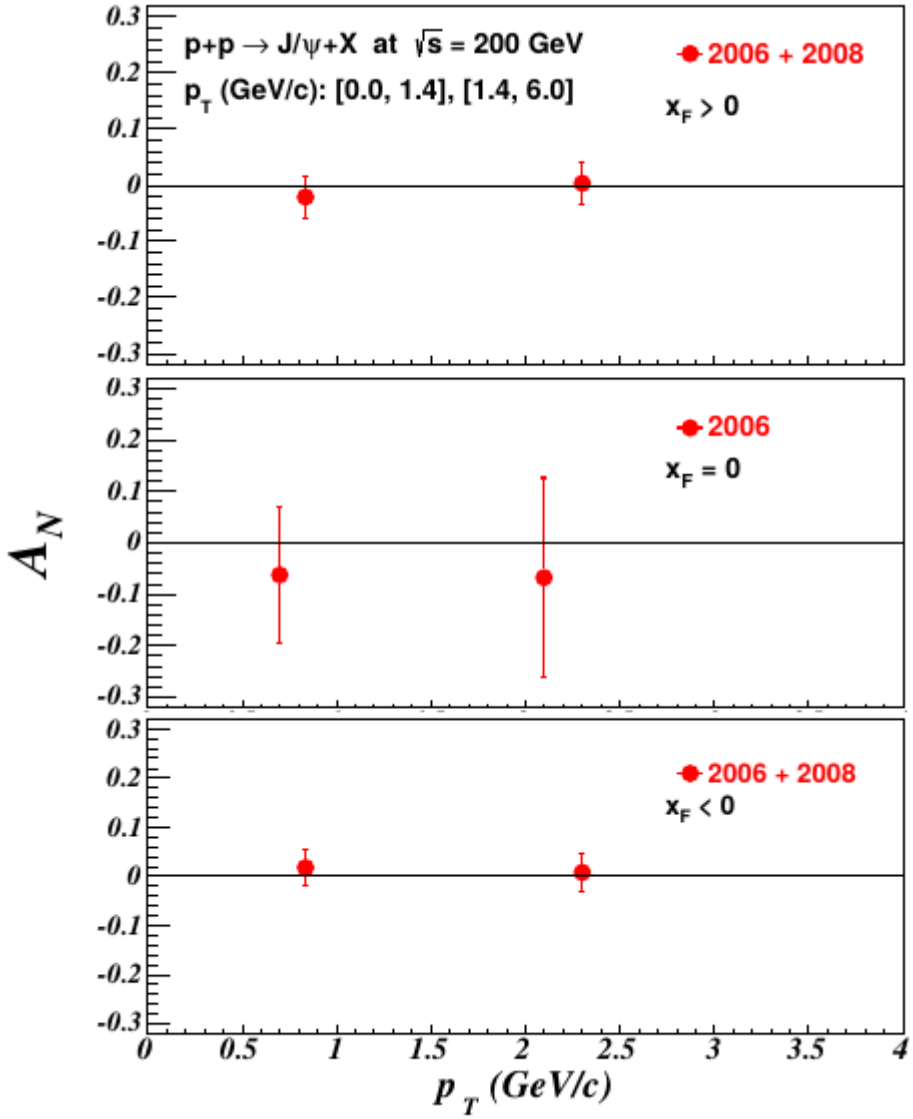
J/ψ transverse SSA at √s = 200 GeV

- PHENIX measured J/ψ production from transversely polarized p+p collisions at 200 GeV at $|y| < 0.35$ and $1.2 < |y| < 2.2$ for $p_T < 6$ GeV/c
- spin asymmetry in the forward region:

  $-0.026 \pm 0.026(\text{stat}) \pm 0.003(\text{sys})$

  consistent with zero





PRD 82 (2010) 112008
PRD 86 (2012) 099904

Summary

- Cross-sections of inclusive J/ψ production measured at $\sqrt{s}$ = 24-500 GeV
  - data corrections done with no polarization assumed
  - p_T differential cross-section agree with CEM and NRQCD calculations
  - p_T integrated yields overpredicted by NRQCD
- Only few measurements done for ψ(2S)
  - p_T integrated yields overpredicted by NRQCD
- ϒ (mostly ϒ(1S+2S+3S)) measurements done at $\sqrt{s}$ = 38-200 GeV
  - Cross-sections agree well with CEM and NRQCD

- Transverse SSA consistent with 0 at $\sqrt{s}$ =200 GeV

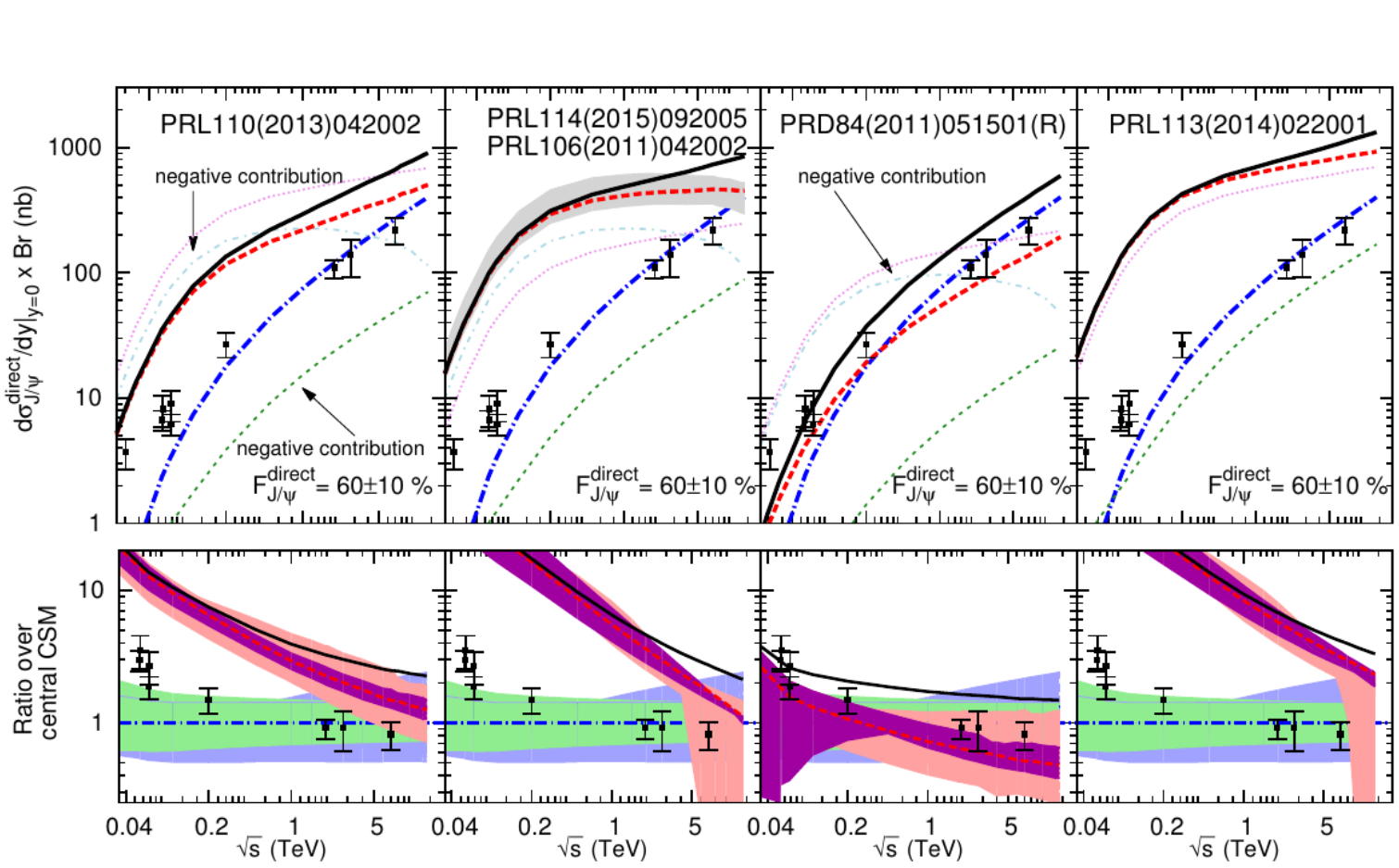
- Quarkonium polarization
  - Measurements done for J/ψ – statistically demanding
  - Feed-down complicates the interpretation
  - Not many measurements for the full angular distribution and in different frames
  - So far hard to distinguish between models
  - Longitudinal polarization observed at RHIC, common x_T trend of λ_θ in HX frame

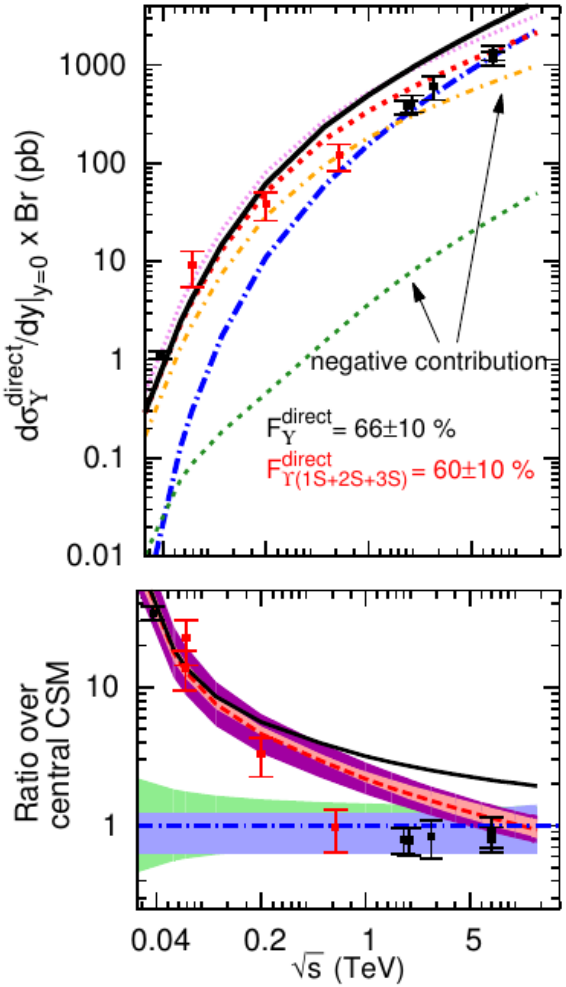
Backup

J/ψ cross-section *vs* √s – model comparison

- direct J/ψ production vs √s

Direct ϒ(1S) production at y=0

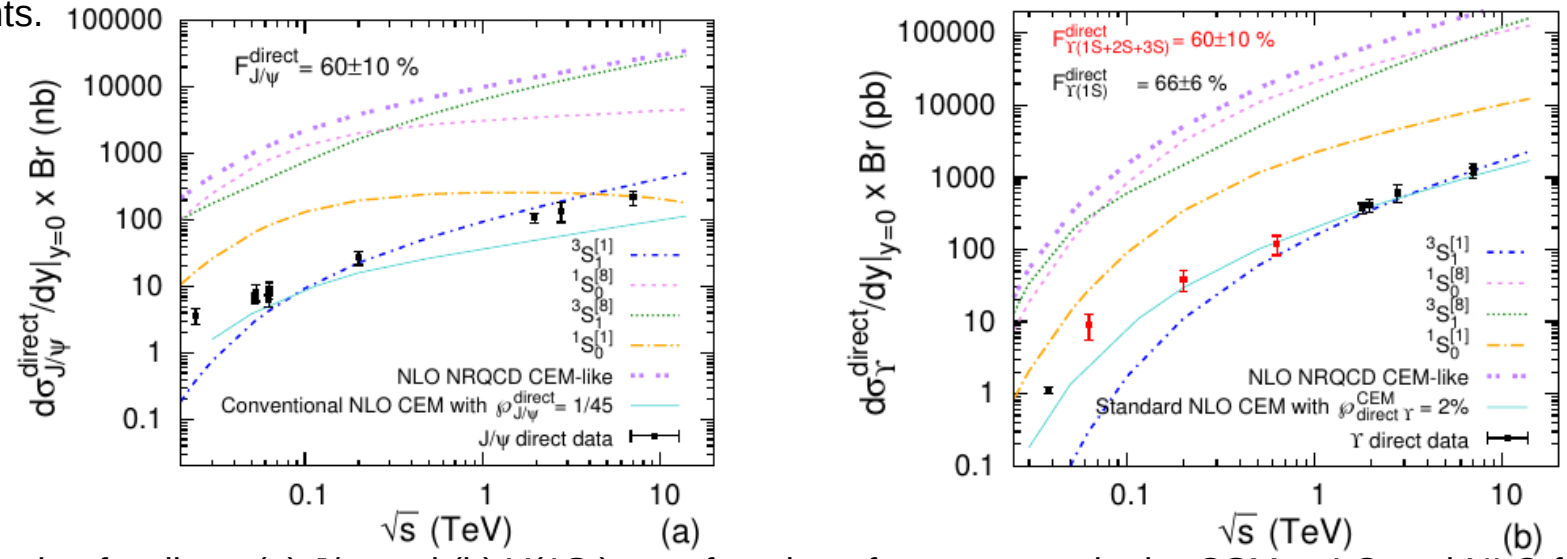




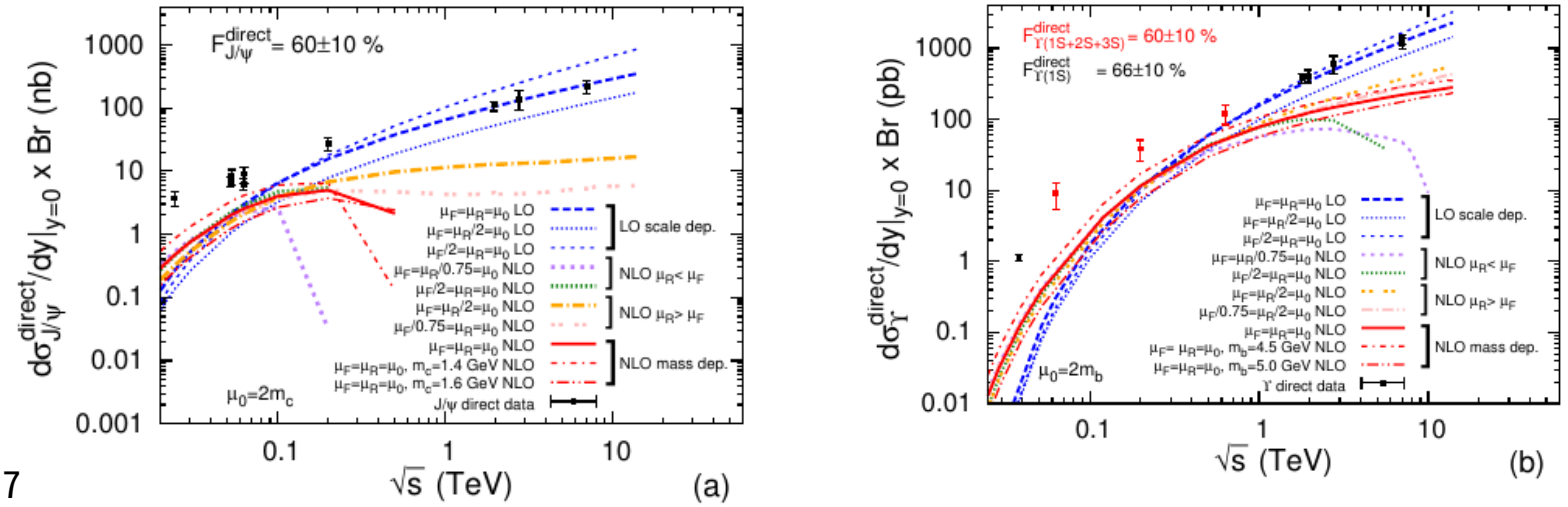
arXiv: 1504.00317

J/ψ and Υ cross-sections vs √s – model comparison

The cross section for direct (a) J/ψ and (b) Υ(1S) as a function of √s from NLO NRQCD using the CEM-like constrained LDMEs assuming a minimal singlet transition. It is compared to the existing experimental measurements.



The cross section for direct (a) J/ψ and (b) Υ(1S) as a function of cms-energy in the CSM at LO and NLO for various choices of the mass and scales compared with the existing experimental measurements.



arXiv: 1504.00317

J/ψ @ √s = 30.6, 52.4, 62.7 GeV ISR

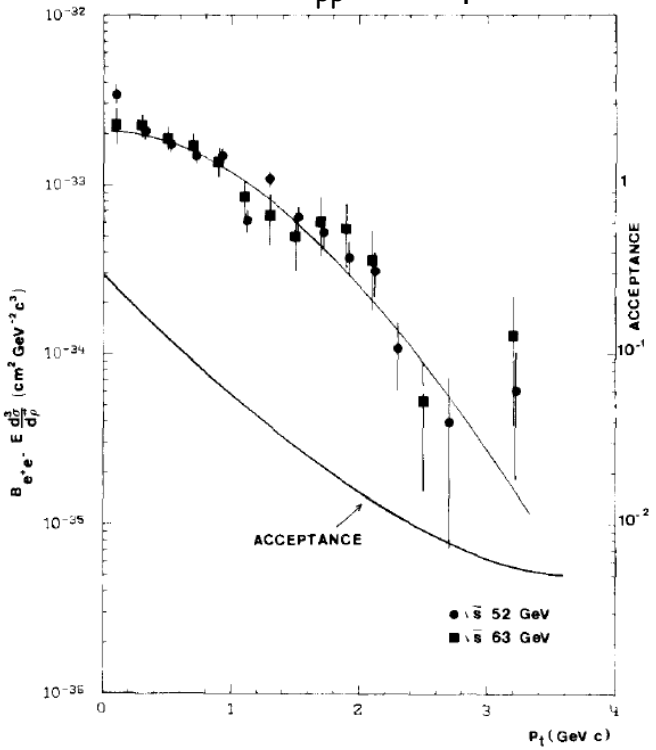
- inclusive $J/\psi \to e^+e^-$
- pp, $|y| < 0.5$
- $B\,\sigma_{y=0}^{30} = (6.58 \pm 1.76) \times 10^{-33}\ cm^2$

  $\sigma_{y=0}^{52} = (10.86 \pm 0.41) \times 10^{-33}\ cm^2$

  $\sigma_{y=0}^{63} = (10.2 \pm 0.7) \times 10^{-33}\ cm^2$

- $\langle p_T \rangle = (1.1 \pm 0.05)\ GeV/c$

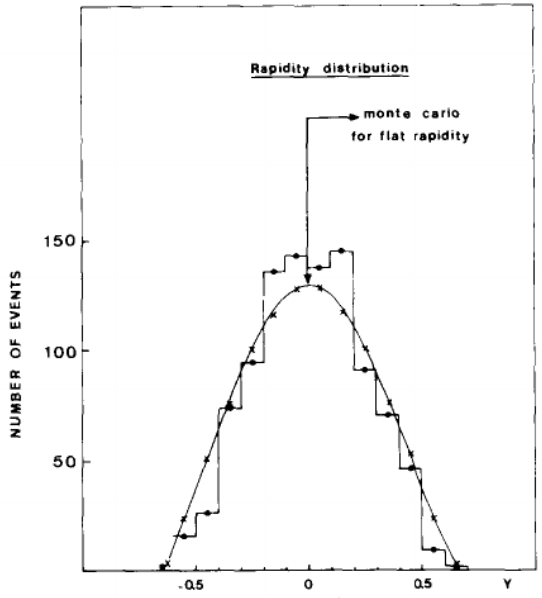
J/ψ BR σ_{pp} *vs* p_T



1978
CERN ISR

Nucl. Phys. B142, 29

J/ψ σ_{pp} *vs* y



(i) The ψ' inclusive production cross section is measured to be:

$$\left.\frac{d\sigma}{dy}\right|_{y=0}(pp \to \psi' + \ldots) = (1.9 \pm 0.7) \cdot 10^{-2}$$

$$\times \left.\frac{d\sigma}{dy}\right|_{y=0}(pp \to J/\psi + \ldots)\frac{B_{ee}(J/\psi)}{B_{ee}(\psi')}\ .$$

J/ψ @ √s = 30, 53, 63 GeV ISR

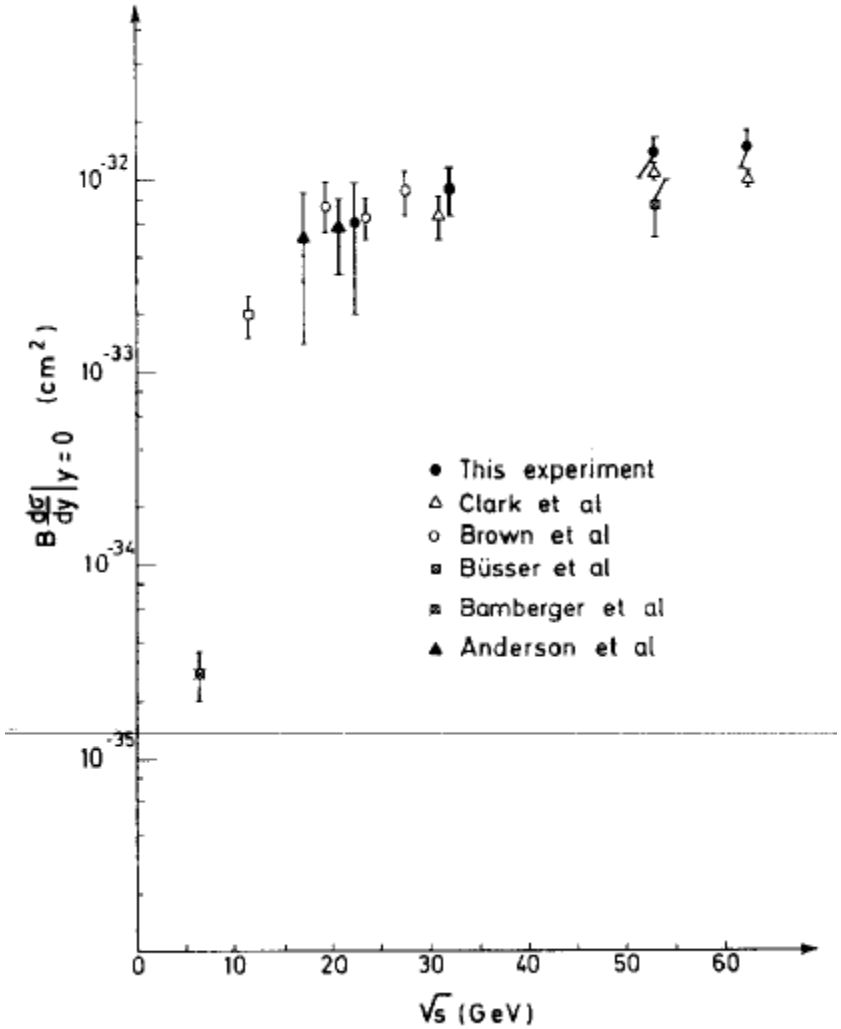
- inclusive $J/\psi \to e^+e^-$

- BR $\sigma_{y=0}^{30} = (9.1 \pm 2.5) \times 10^{-33}$ cm^2
  BR $\sigma_{y=0}^{53} = (13.6 \pm 3.1) \times 10^{-33}$ cm^2
  BR $\sigma_{y=0}^{63} = (14.8 \pm 3.3) \times 10^{-33}$ cm^2
- $\langle p_T \rangle_{30} = (1.14 \pm 0.12)$ GeV/c
  $\langle p_T \rangle_{53} = (1.39 \pm 0.05)$ GeV/c
  $\langle p_T \rangle_{63} = (1.29 \pm 0.05)$ GeV/c

$$E(d^3\sigma/dp^3) = A \exp(-bp_T)$$

- x-section rises by a factor of 1.5 from 27.4 to 63 GeV
- No polarization, alpha consistent with 0

J/ψ BR σ_{pp} at y=0 *vs* √s



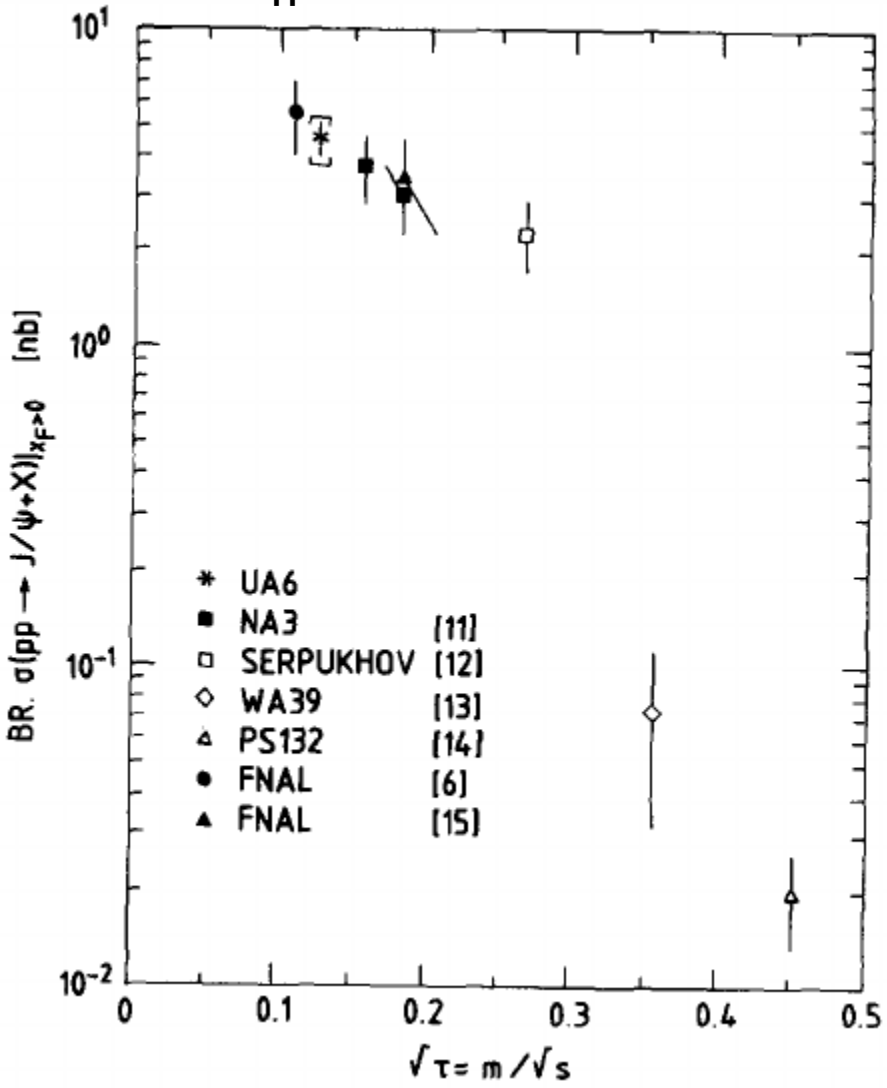
1980
CERN ISR

Phys.Lett.
B 91, 481

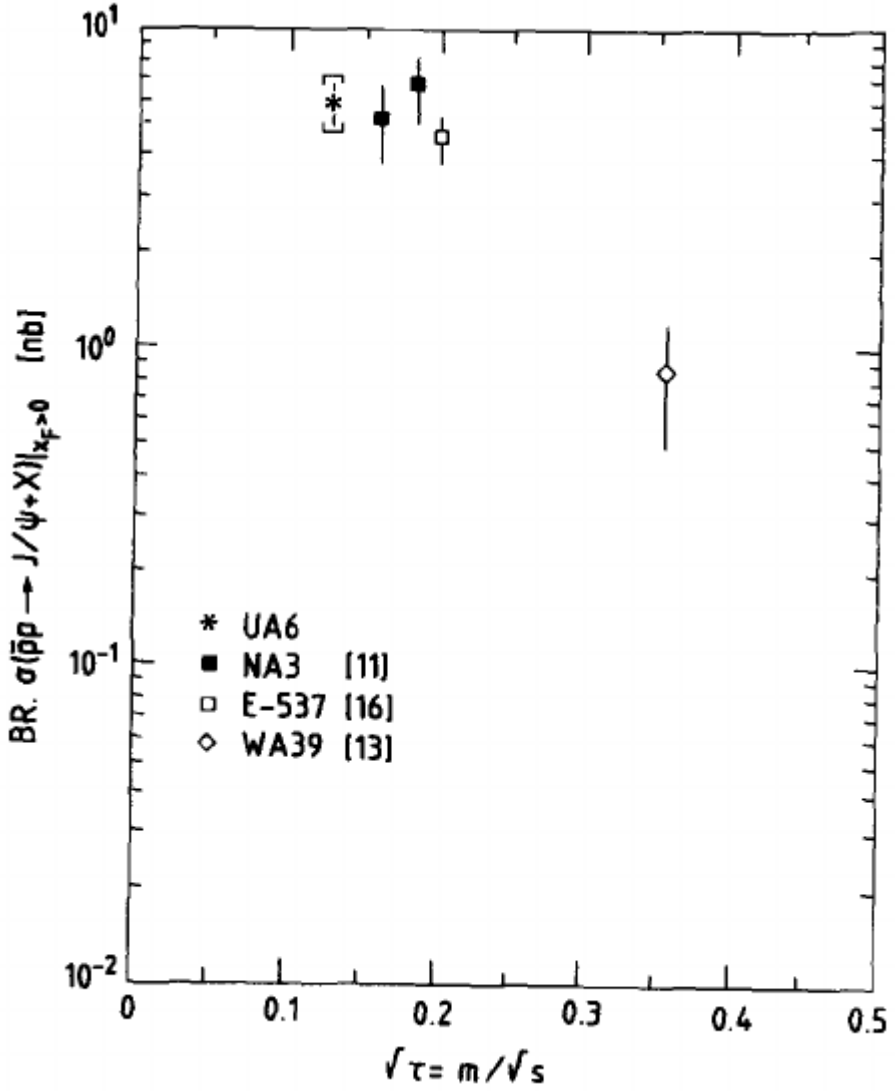
J/ψ @ √s = 24.3 GeV

UA6

BR σ_{pp} at $x_F > 0$ *vs* $\sqrt{\tau} = m/\sqrt{s}$



BR $\sigma_{\bar{p}p}$ at $x_F > 0$ *vs* $\sqrt{\tau} = m/\sqrt{s}$



1990
CERN SPS

Phys.Lett.
B 252, 505

J/ψ @ √s = 24.3 GeV

UA6

- inclusive $J/\psi \to e^+e^-$
- p and $\bar{p}$, hydrogen target
- $0 < y < 1.2$
- $\sigma_{\bar{p}p} = (5.1 \pm 0.7 \pm 0.4)$ nb

  $\sigma_{pp} = (3.9 \pm 0.5 \pm 0.3)$ nb
- $\langle p_T \rangle_{\bar{p}p} = (0.9 \pm 0.2)$ GeV/c

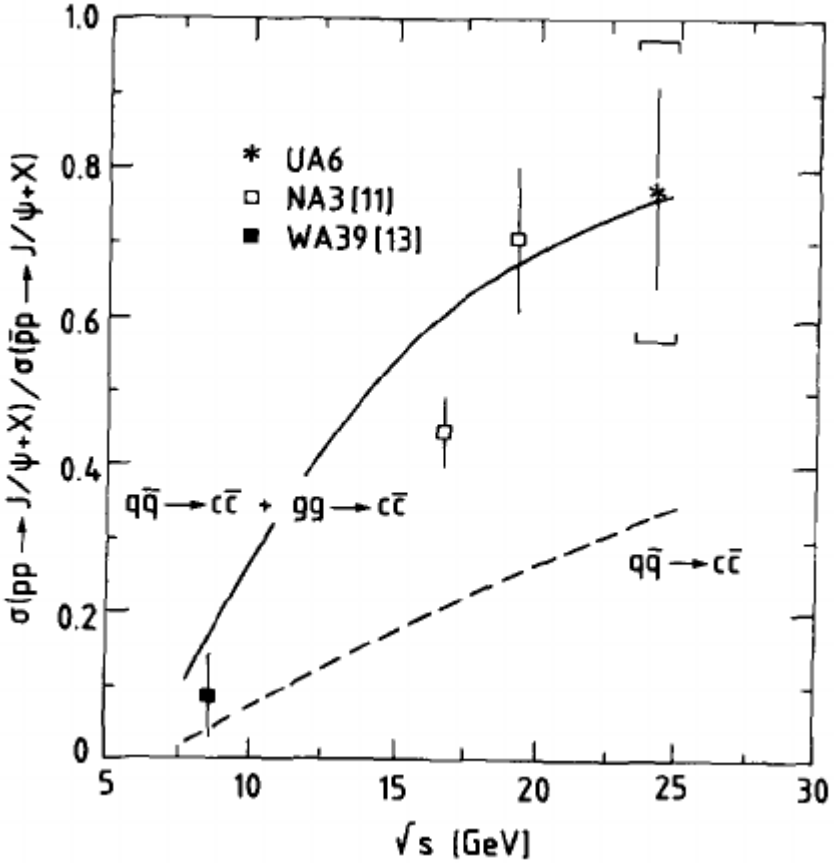
  $\langle p_T \rangle_{pp} = (1.1 \pm 0.2)$ GeV/c
- forward hemisphere, $x_F > 0$:

  $\sigma_{\bar{p}p} = (5.9 \pm 0.8 \pm 0.4)$ nb

  $\sigma_{pp} = (4.5 \pm 0.5 \pm 0.3)$ nb

  $\sigma_{pp}/\sigma_{\bar{p}p} = 0.76 \pm 0.14 \pm 0.06$
- gluon contributions dominates the hadroproduction

$\sigma_{pp}/\sigma_{\bar{p}p}$ at $x_F > 0$ *vs* $\sqrt{s}$



1990
CERN SPS

Phys.Lett.
B 252, 505

Υ @ $\sqrt{s}$ = 52, 62 GeV

ISR

- Inclusive $\Upsilon(9.5) \to e^+e^-$

1977
CERN ISR

Phys.Lett.
B 72, 273

$$B_{ee}\left.\frac{d\sigma}{dy}\right|_{y=0} = 0.28 \pm 0.14 \times 10^{-34}\ \text{cm}^2 \text{ at } \sqrt{s} = 52\ \text{GeV}$$

and

$$B_{ee}\left.\frac{d\sigma}{dy}\right|_{y=0} = 0.59 \pm 0.34 \times 10^{-34}\ \text{cm}^2 \text{ at } \sqrt{s} = 62\ \text{GeV}$$

- $\langle p_T \rangle = (0.98 \pm 0.37)$ GeV/c

Υ @ $\sqrt{s}$ = 53, 63 GeV

ISR

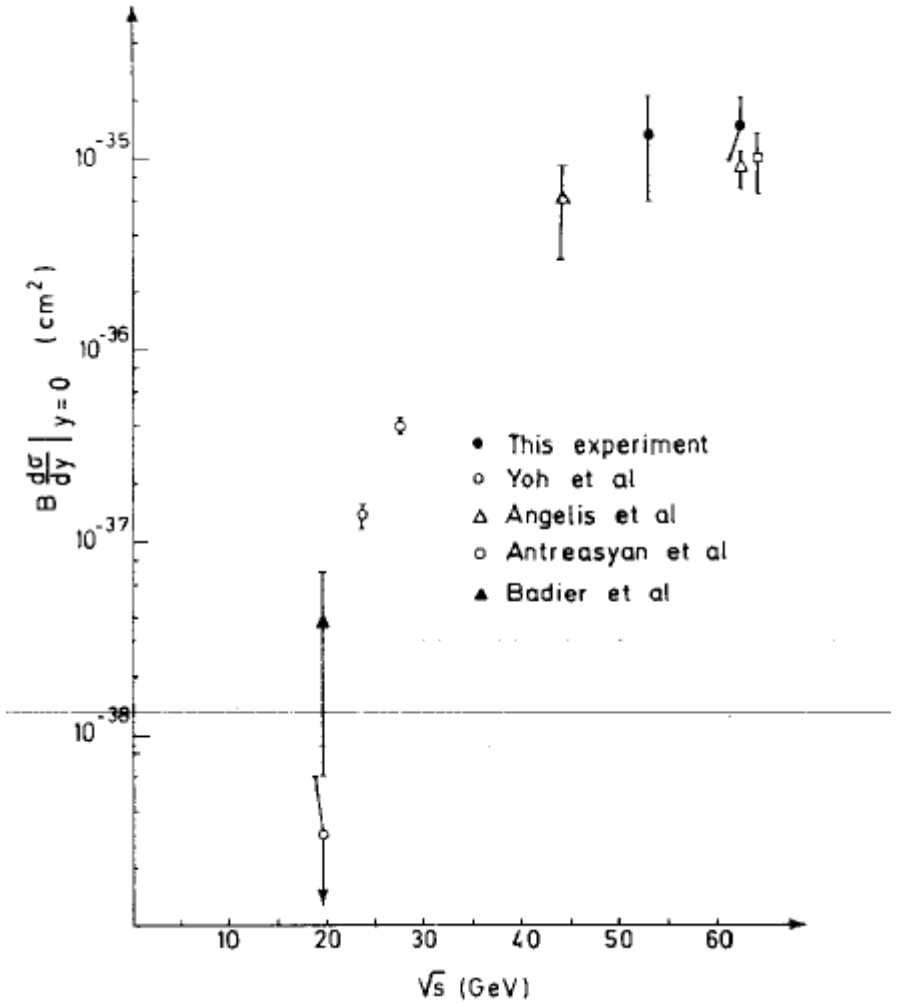
- inclusive $\Upsilon \to e^+e^-$
- pp
- $\sigma_{y=0}^{53} = (13.5 \pm 7.4) \times 10^{-36}$ cm^2
  $\sigma_{y=0}^{63} = (15.2 \pm 5.5) \times 10^{-36}$ cm^2
- $\langle p_T \rangle_{63} = (1.75 \pm 0.19)$ GeV/c

- x-section rises by a factor of 30 from 27.4 to 63 GeV

$$dN/d\cos\theta \sim 1 + \alpha \cos^2\theta$$

$$\alpha = 0.31 \pm 0.28$$

Υ σ_{pp} at y=0 *vs* $\sqrt{s}$



1980
CERN ISR

Phys.Lett.
B 91, 481