HEAVY QUARKONIUM
UPSILON PRODUCTION IN HADRON COLLIDER

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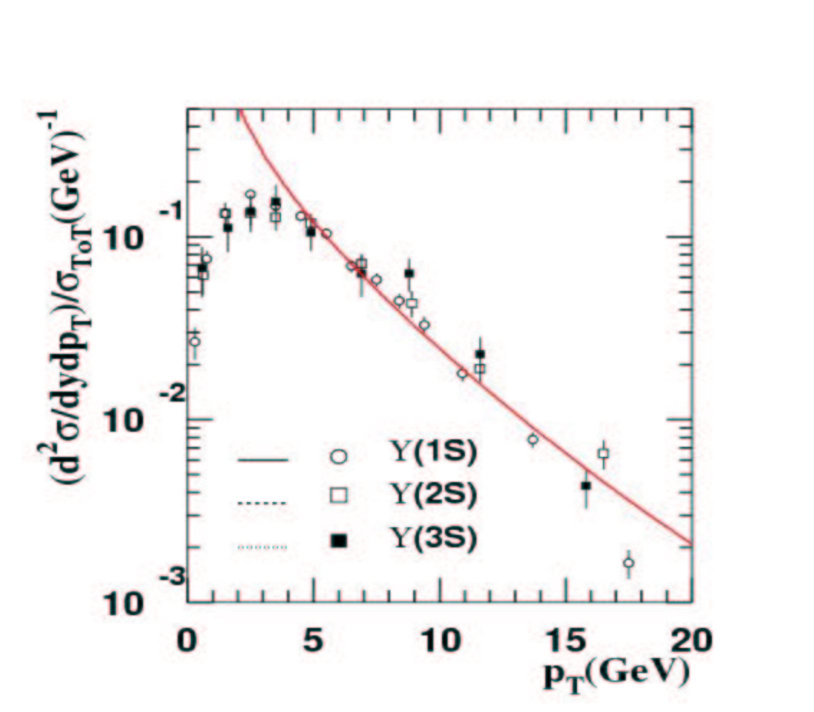
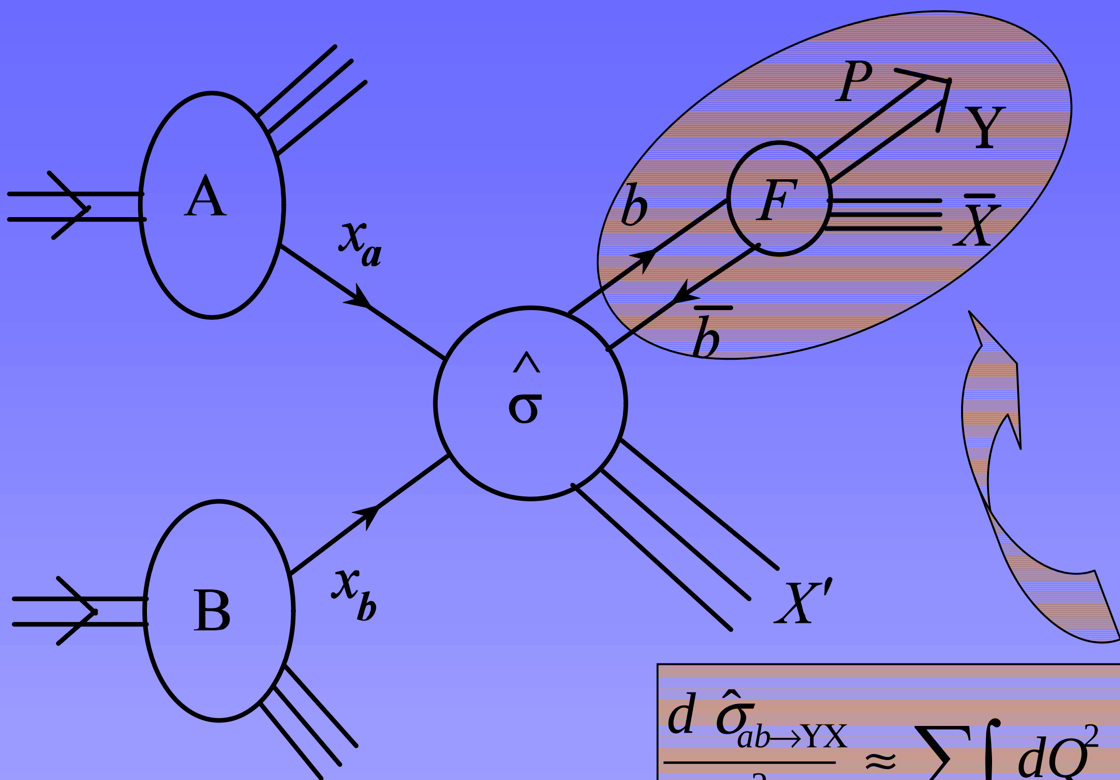
Motivation — Upsilon new data in Tevatron

Perturbation Theory of QCD are very successful in high p_T
New Data from Tevatron test QCD to a new level of accuracy.

p_T ~ small,
Soft gluon radiation
Perturbative value
— infinite
Need to be resumed
to all orders in α_s



Factorization in Upsilon production — two steps



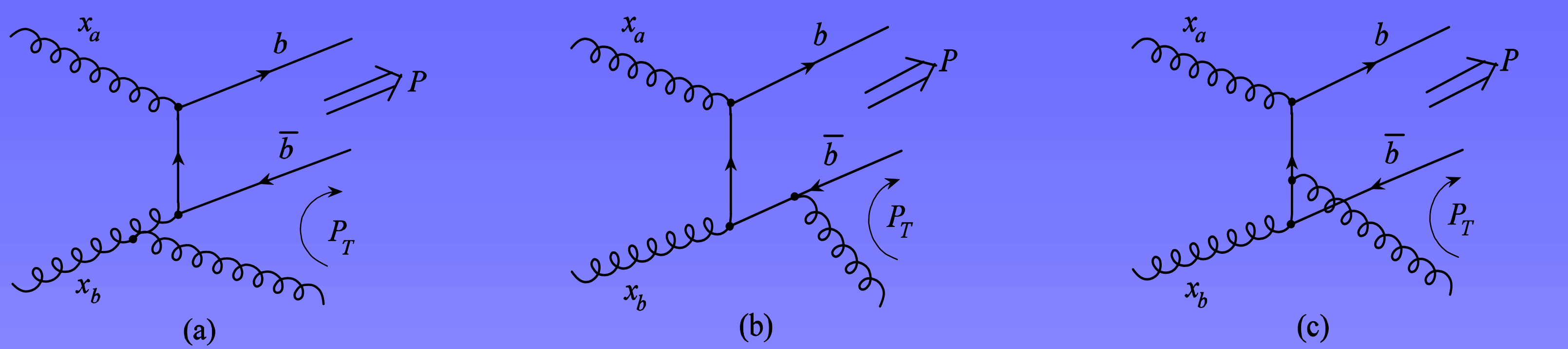
$$\frac{d\hat{\sigma}_{ab\to \Upsilon X}}{dp_T^2\,dy} \approx \sum_{[b\bar{b}]} \int dQ^2 \left[\frac{d\hat{\sigma}_{ab\to[b\bar{b}](Q)X}}{dQ^2\,dp_T^2\,dy}\right] F_{[b\bar{b}]\to \Upsilon X}(Q^2)$$

$$\frac{d\sigma_{AB\to \Upsilon X}}{dp_T^2\,dy} = \sum_{a,b} \int dx_a\,\phi_{a/A}(x_a)\;dx_b\,\phi_{b/B}(x_b)\;\frac{d\hat{\sigma}_{ab\to \Upsilon X}}{dp_T^2\,dy}$$

$$\frac{d\sigma_{AB\to YX}}{dQ^2\,dp_T^2\,dy} = \sum_{a,b}\int dx_a \phi_{a/A}(x_a)\; dx_b \phi_{b/B}(x_b) \sum_{[b\bar{b}]}\left[\frac{d\hat{\sigma}_{ab\to[b\bar{b}](Q)X'}}{dQ^2\,dp_T^2\,dy}\right] F_{[b\bar{b}]\to \Upsilon \bar{X}}(Q^2)$$

$$\frac{d\sigma_{AB\to \Upsilon X}}{dQ^2\,dp_T^2\,dy} \approx \begin{cases} \dfrac{d\sigma^{resum}_{AB\to \Upsilon X}}{dQ^2\,dp_T^2\,dy} & p_T < p_{T_M} \\[2ex] \dfrac{d\sigma^{pert}_{AB\to \Upsilon X}}{dQ^2\,dp_T^2\,dy} & p_T \geq p_{T_M} \end{cases}$$

Resummation in small p_T



Absorbed into $F_{[b\bar{b}]\to \Upsilon \bar{X}}(Q^2)$

No included for Tevatron data

Resummed an infinite series of soft gluon emissions

$$\sigma \approx \sigma^{(0)} e^{-S\left(\ln \frac{M_Y^2}{p_T^2}\right)}$$

Collins, Soper and Sterman (CSS) b-space approach

$$\frac{d\sigma^{(resum)}_{AB\to[b\bar{b}]X}}{dQ^2\,dp_T^2\,dy} = \frac{1}{(2\pi)^2}\int d^2b\; e^{i\,\vec{p}_T\bullet\vec{b}}\,W_{AB\to[b\bar{b}]X}(b,\;Q,\;x_A,\;x_B)$$

$$\int \frac{db}{2\pi}\;J_0(p_T b)\;bW_{AB\to[b\bar{b}]X}(b,\;Q,\;x_A,\;x_B)$$

Two subprocesses: $gg \to b\bar{b}$ and $q\bar{q} \to b\bar{b}$

$$W_{AB\to[b\bar{b}](Q)}(b,\;Q,\;x_A,\;x_B) \equiv \sum_q w_{q\bar{q}}(b,\;Q,\;x_A,\;x_B)\;\frac{d\hat{\sigma}^{(LO)}_{q\bar{q}\to[b\bar{b}](Q)}}{dQ^2}$$

$$+\;w_{gg}(b,\;Q,\;x_A,\;x_B)\;\frac{d\hat{\sigma}^{(LO)}_{gg\to[b\bar{b}](Q)}}{dQ^2}$$

b < 1 GeV⁻¹

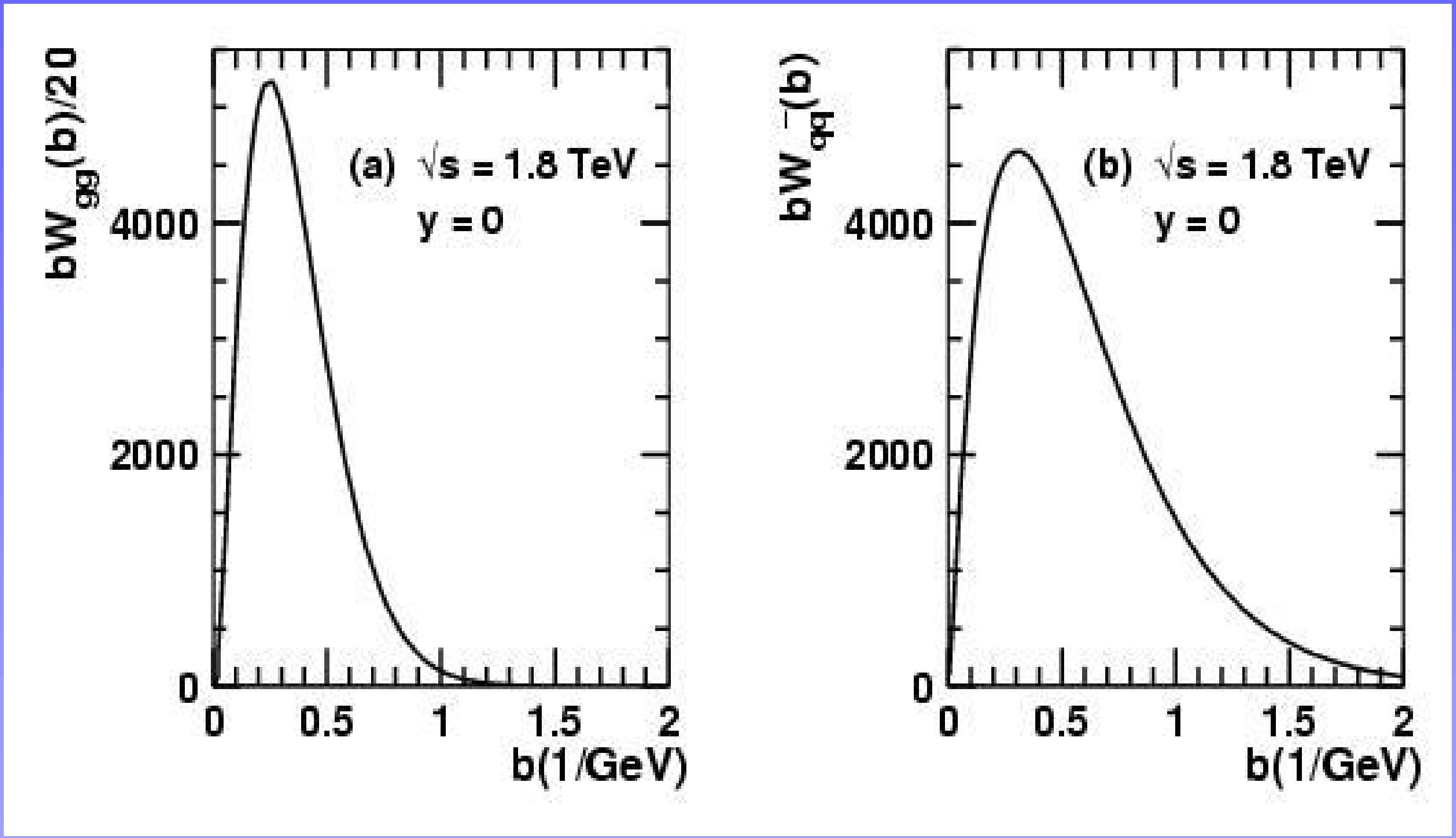
$$w_{q\bar{q}}(b,\ Q,\ x_A,\ x_B) \equiv e^{-S_q(b,\ Q)} w_{q\bar{q}}\left(b,\ \frac{c}{b},\ x_A,\ x_B\right)$$

$$w_{gg}(b,\ Q,\ x_A,\ x_B) \equiv e^{-S_g(b,\ Q)} w_{gg}\left(b,\ \frac{c}{b},\ x_A,\ x_B\right)$$

$$S_{q,\ g}(b,\ Q) = \int_{c^2/b^2}^{Q^2} \frac{d\mu^2}{\mu^2}\left[\ln\left(\frac{Q^2}{\mu^2}\right) A_{q,\ g}(\alpha_s(\mu)) + B_{q,\ g}(\alpha_s(\mu))\right]$$

$$w_{ij}\left(b,\ \frac{c}{b},\ x_A,\ x_B\right) = f_{i/A}\left(x_A,\ \mu,\ \frac{c}{b}\right) f_{j/B}\left(x_B,\ \mu,\ \frac{c}{b}\right)$$

$$f_{i/A}\left(x_A,\ \mu,\ \frac{c}{b}\right) = \sum_a \int_{x_A}^{1} \frac{d\xi}{\xi}\ \phi_{a/A}(\xi,\ \mu)\ C_{a\to i}\left(\frac{x_A}{\xi},\ \mu,\ \frac{c}{b}\right)$$



$bW_{gg}(b)/20$
(a) √s = 1.8 TeV
y = 0
4000
2000
0
0
0.5
1
1.5
2
b(1/GeV)
$bW_{q\bar{q}}(b)$
(b) √s = 1.8 TeV
y = 0
4000
2000
0
0
0.5
1
1.5
2
b(1/GeV)

$$W_{ij}(b, Q, x_A, x_B) = \begin{cases} W_{ij}(b, Q, x_A, x_B) & b \le b_{\max} \\ W_{ij}(b, Q, x_A, x_B)\, F_{ij}^{NP}(b, Q, b_{\max}) & b > b_{\max} \end{cases}$$

$$F_{ij}^{NP} = \exp\left\{ -\ln\left(\frac{Q^2 b_{\max}^2}{c^2}\right) \left[g_1\left((b^2)^{\alpha} - (b_{\max}^2)^{\alpha} \right) - g_2 (b^2 - b_{\max}^2) - \bar{g}_2 (b^2 - b_{\max}^2) \right] \right\}$$

g_1 and α are from x_A and x_B dependences

fixed by continuous

g_2 and $\bar{g}_2$ are from power corrections

fixed by fitting data

Color evaporation model (CEM)   hep-ph/0404158

Ignore detail of the formation of Upsilon from Quarkonium

$$F_{[b\bar{b}]\to\Upsilon}(Q^2) = \begin{cases} C_\Upsilon & M_\Upsilon^2 \le Q^2 \le M_B^2 \\ 0 & otherwise \end{cases}$$

$$\frac{d\hat{\sigma}^{CEM}_{ab\to\Upsilon X}}{dp_T^2\,dy} \approx C_\Upsilon \int_{M_\Upsilon^2}^{M_B^2} dQ^2 \left[\frac{d\hat{\sigma}_{ab\to[b\bar{b}](Q)}}{dQ^2\,dp_T^2\,dy}\right]$$

CDF data

Non-relativistic QCD Model (NRQCD)

$$\frac{d\hat{\sigma}_{ab\to\Upsilon X}}{dp_T^2\,dy} \approx \sum_{[b\bar{b}]} \left[\frac{d\hat{\sigma}_{ab\to[b\bar{b}](Q)X'}}{dQ^2\,dp_T^2\,dy}\left(Q^2 = M_\Upsilon^2\right)\right] \underbrace{\int dQ^2\, F_{[b\bar{b}]\to\Upsilon X}(Q^2)}_{\left\langle \hat{O}_{[b\bar{b}]}\right\rangle}$$

$$\left[b\bar{b}\right] \Rightarrow {}^1S_0^{[1,8]},\ {}^3S_1^{[1,8]},\ {}^1P_1^{[1,8]}\ \cdots$$

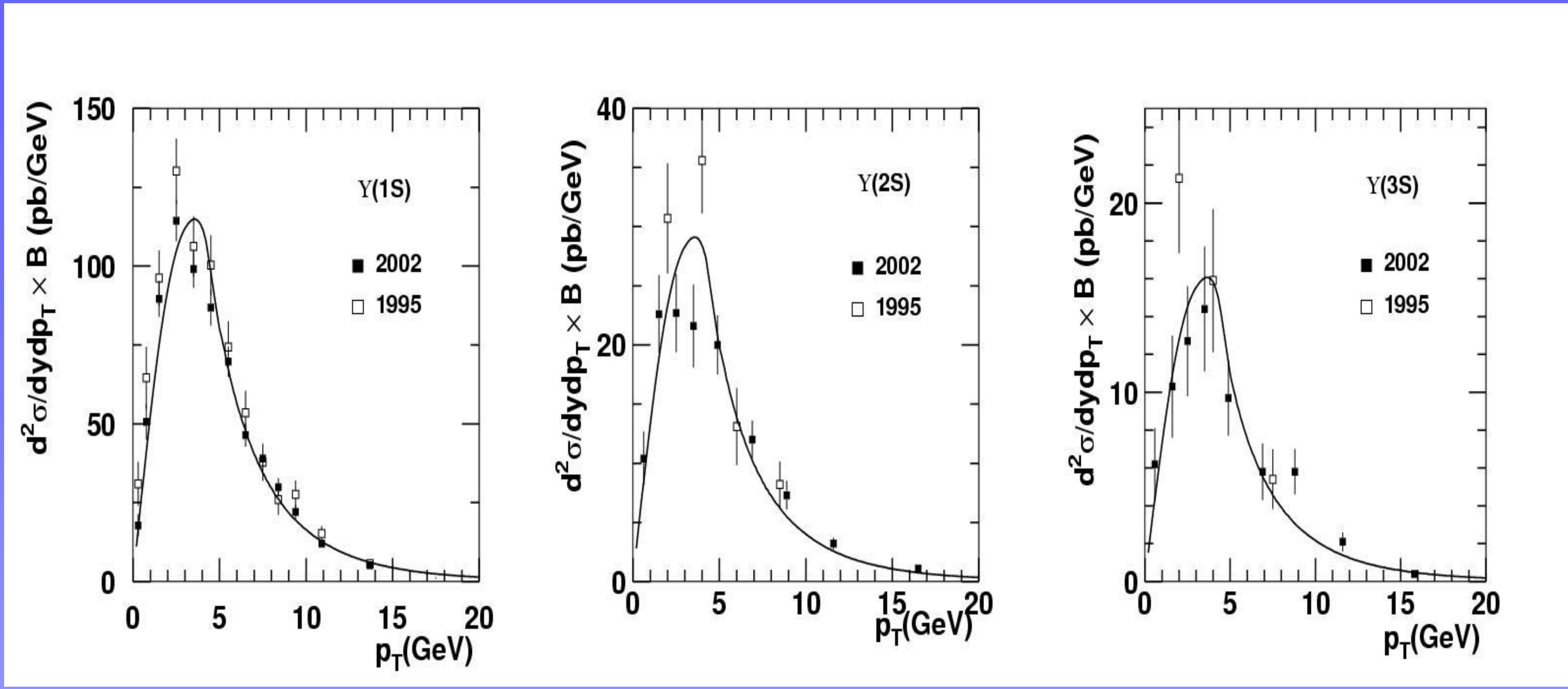
Upsilon results in color evaporation model (CEM)

$$\frac{d\sigma_{AB\to \Upsilon(nS)X}}{dp_T^2 dy} = C_\Upsilon \int_{M^2_{\Upsilon(nS)}}^{4M_B^2} dQ^2 \sum_{a,b} \int dx_a \phi_{a/A}(x_a)\ dx_b \phi_{b/B}(x_b)\ \frac{d\hat{\sigma}_{ab\to[b\bar{b}](Q)X}}{dQ^2 dp_T^2 dy}$$

order of α_s corrections

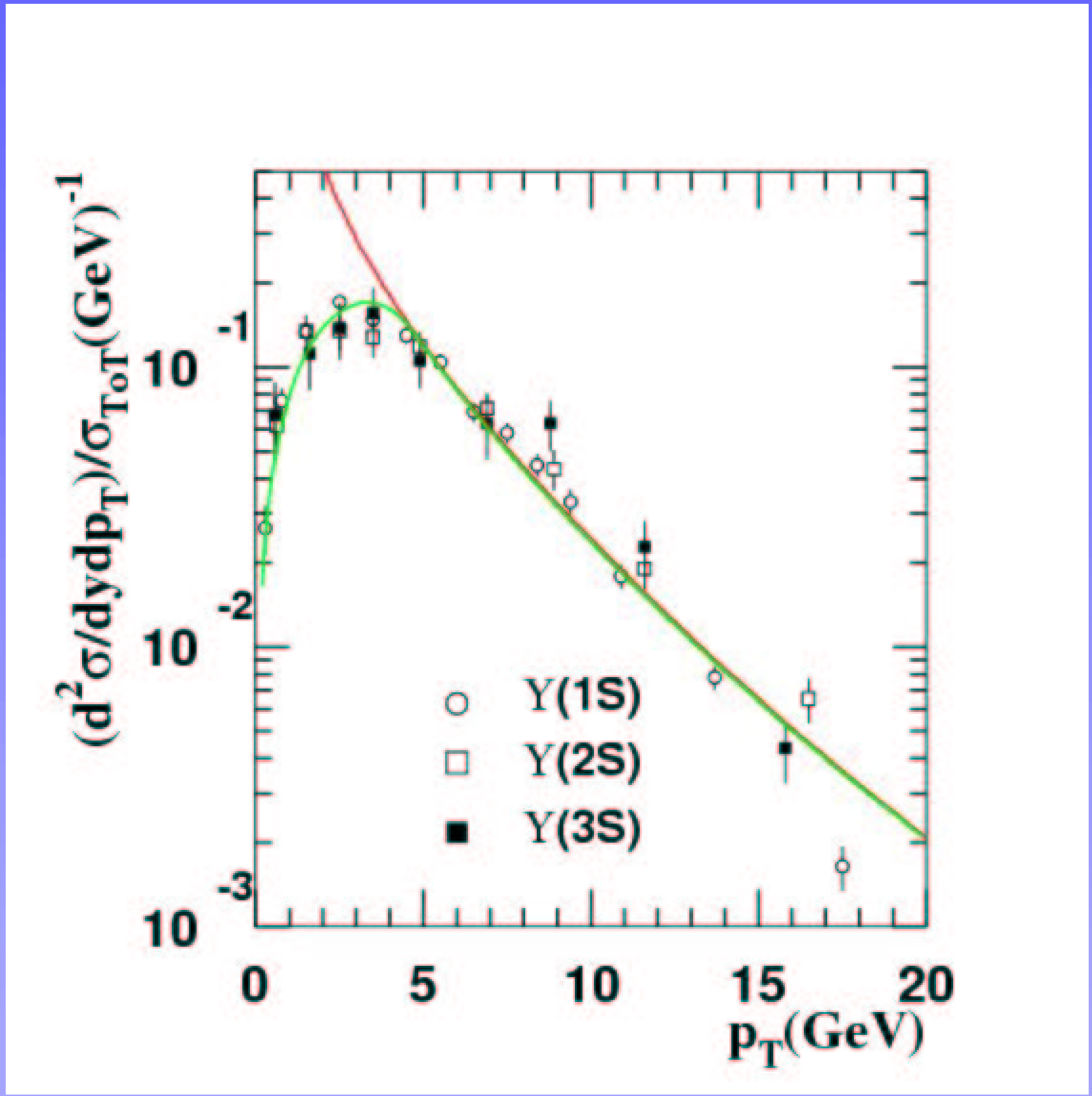
$$\frac{d\sigma_{AB\to\Upsilon(nS)X}}{dp_T^2 dy} \approx \begin{cases} \kappa_\Upsilon \dfrac{d\sigma^{resum}_{AB\to\Upsilon(nS)X}}{dp_T^2 dy} & p_T < p_{T_M} \\ \dfrac{d\sigma^{pert}_{AB\to\Upsilon(nS)X}}{dp_T^2 dy} & p_T \geq p_{T_M} \end{cases}$$

resummed and perturbative parts match at $p_{T_M} \leq M_\Upsilon$



$p_{T_M} \sim 4.27\ GeV,$	
$\kappa_\Upsilon = 1.22 \pm 0.02$	

	C_Υ
Υ(1S)	0.044
Υ(2S)	0.040
Υ(3S)	0.041


$(d^2\sigma/dydp_T)/\sigma_{ToT}(GeV)^{-1}$
10^{-1}
10^{-2}
10^{-3}
0
5
10
15
20
p_T(GeV)
Υ(1S)
Υ(2S)
Υ(3S)

Conclusion

- Upsilon is derived from a pair of bottom quarks.
- resummed large logarithmic contributions from initial-state gluon showers at small p_T.
- Results are in good agreement with data from Tevatron.