B Physics at CDF (including onium production)

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Collider Physics Meeting
February 27, 2002
KEK

Introduction

First 2 fb^{-1} of Run II (2001 - 2004)

Tevatron Run II has just started.
Expect to collect 2 fb^{-1} of data in 2 years.
20-fold increase from the previous run.

CDF detector underwent a major upgrade.
Maintained strengths (momentum resolution, lepton ID, vertexing).
B physics capability enhanced (e.g. silicon vertex trigger).

We have pretty good ideas about what we will be doing in the area of B physics.

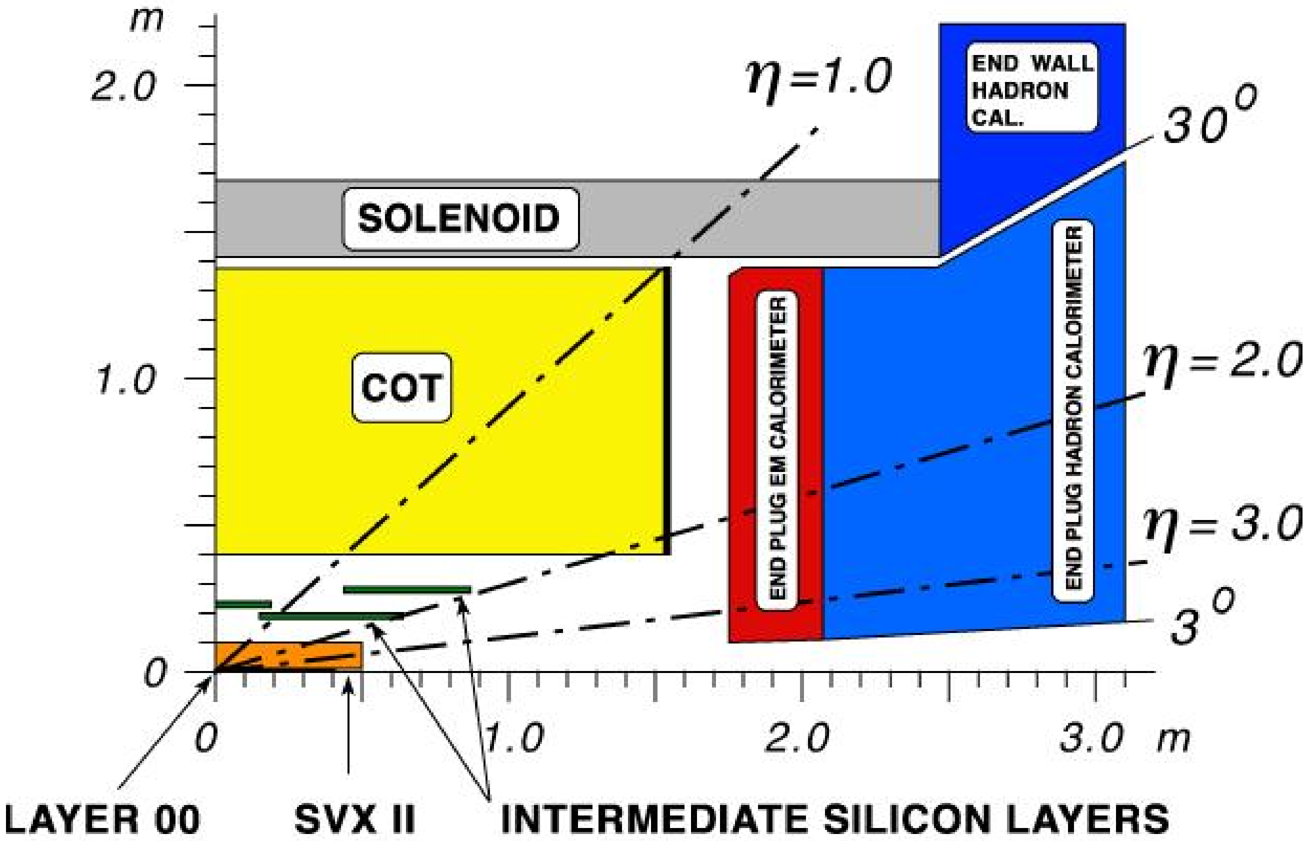
Tevatron B Physics Workshop

Held in Sept 1999 and Feb 2000.
Covers Run II (CDF, D0) and beyond (BTeV).
Workshop write-up is finally available as
hep-ph/0201071

CDF (Tevatron) vs. $\Upsilon(4S)$

- $\times 10^4$ higher $b\bar{b}$ cross section at Tevatron
  - Worse S/N ($\sim 2\%$ for $p_T > 5$ GeV/c).
  - Specialized trigger crucial.
  - Flavor tagging very hard.
- B_s^0 (also B_c^+, Λ_b^0 ...) as well as B^0, B^+
  - $B_s^0 \bar{B}_s^0$ mixing for CKM test. Also non-SM CP?
- Central geometry (CDF/D0) advantages
  - Particles more spread out. CDF demonstrates full B reconstruction.
  - Proper decay time resolution fine after p_T cuts ($\beta\gamma \sim 2$ to 4). $\sigma_t \sim 45$ fs (15 μm) for B_s^0 mixing.
  - Beam spot at Tevatron small, $\sim 24 \times 24$ μm in transverse to beam.
    Allows for impact parameter trigger (SVT).
- CDF vs. D0
  - Both have undergone major upgrades. D0 now has a magnet, but CDF BL^2 larger.
  - Differences in:
    CDF particle ID from TOF and dE/dx
    CDF uses deadtimeless SVX readout chip $\Rightarrow$
    40 kHz into level-2 SVX trigger (D0 10 kHz).
    Bandwidth for $b\bar{b} \to h^+h^-X$, 100 nb to DAQ.

CDF Run-II Detector



- Charged particle tracking

  Central Outer Tracker : 30 k sense wires.

  $\sigma(p_T)/p_T = 0.0008\, p_t$ for $|\eta| < 1$.

  Relativistic rise dE/dx.

  SVX : 700 k channels (r-φ-z), 15 readouts per track.

  L00 at $R = 1.5$ cm (r-φ only).

  typical proper time $\sigma(t) = 45$ fs.

- Muon coverage increased by $\times 1.7$.

  $p_T > 1.4$ GeV/c, $|\eta| < 1.5$.

- New scintillating plug calorimeter.

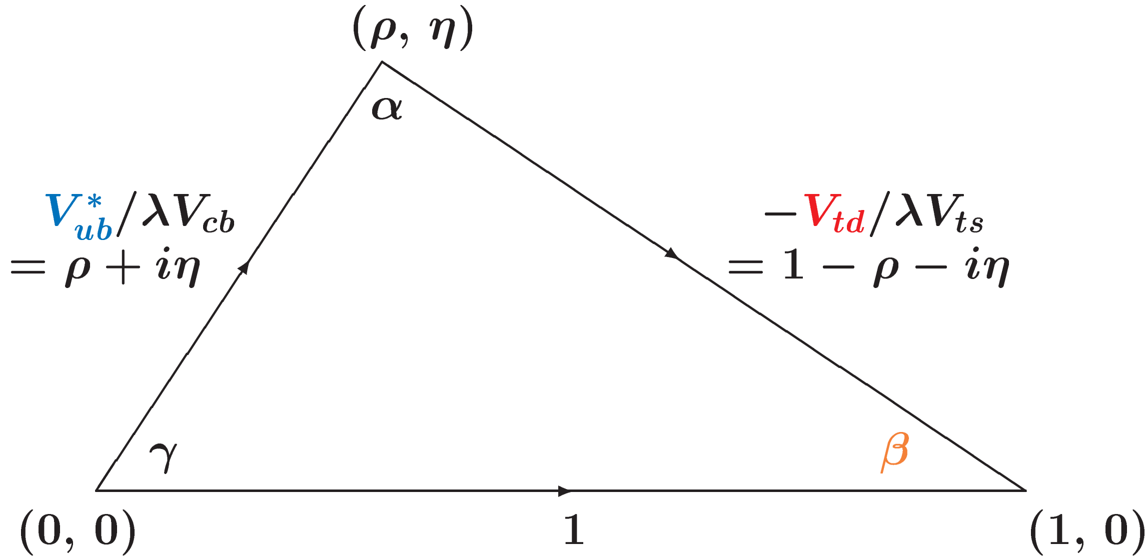
  electron ID.

- TOF particle ID, $|\eta| < 1$.

CKM Matrix and Unitarity

$$V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \simeq \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

$$V^*_{ud}V_{td} + V^*_{us}V_{ts} + V^*_{ub}V_{tb} \simeq V_{td} + \lambda V_{ts} + V^*_{ub} = 0$$



- $|V_{cb}|$ from $b \to c\ell\nu$, $|V_{ub}|$ from $b \to u\ell\nu$.
- $|V_{td}|$ from Δm_d, but large QCD uncertainties.
- Use ratio to partially cancel the uncertainties:

$$\frac{\Delta m_s}{\Delta m_d} = \left|\frac{V_{ts}}{V_{td}}\right|^2 \frac{M_{B_s}}{M_{B_d}} \xi^2 \quad (\xi = 1.17 \pm 0.06, \text{S. Aoki 1999})$$

- Present limit on Δm_s (95% C.L.)

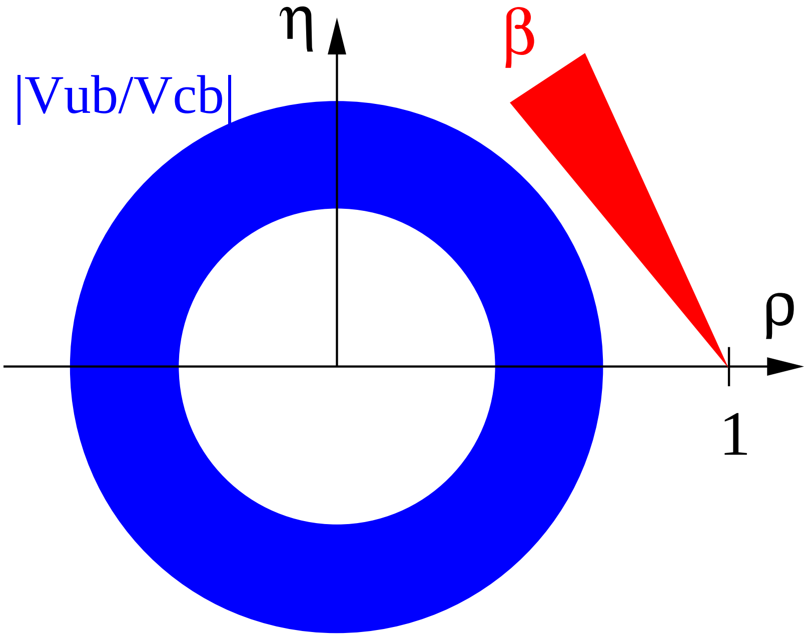
$$\frac{\Delta m_s}{\Delta m_d} > \frac{14.6}{0.494} \implies \frac{|V_{td}|}{\lambda |V_{ts}|} < 0.97 \pm 0.06.$$

- Angle β from $B^0/\bar{B}^0 \to J/\psi K^0_S$.

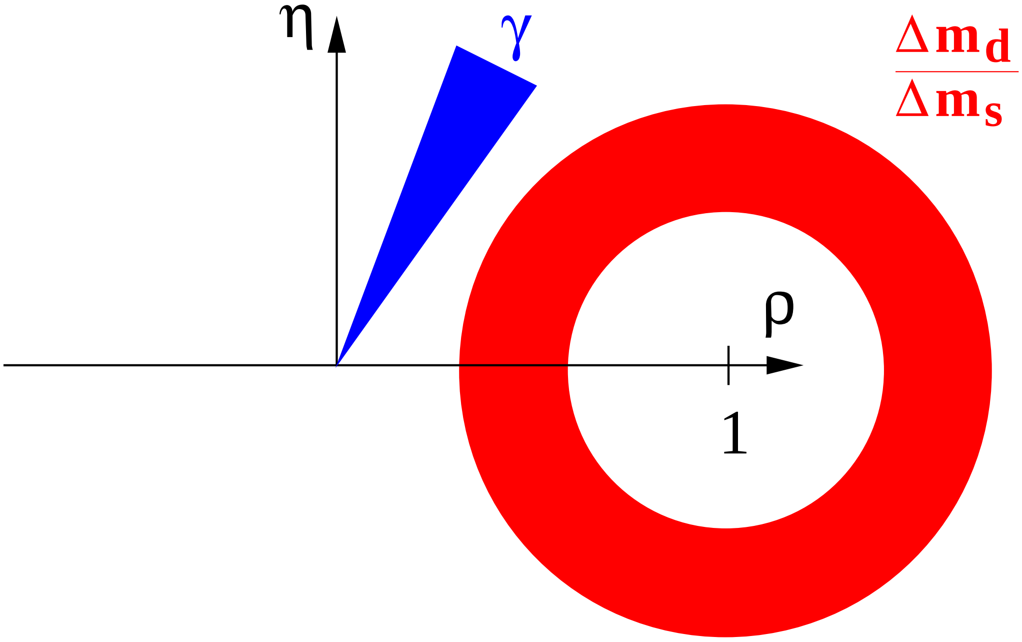
Over-constrain the triangle and check the consistency!

Will New Physics Show Up?

When you will have measured angles β and γ, and sides $|V_{td}/V_{ts}|$ and $|V_{ub}/V_{cb}|$ precisely enough, things may turn out to be like this:



CP violating New Physics in mixing



CP conserving New Physics in mixing

Tevatron Status

Run II Status (March 2001 -)

36×36 bunches of p's and $\bar{p}$'s.
New 150 GeV Main Injector.

- Peak lum of 5×10^{30} achieved in June 2001.

<u>Plan as of summer 2001</u> :

- Expect 1×10^{31} by Sept 15.
- Peak lum of $4 - 5 \times 10^{31}$ by Jan 2002.
  $4.5 - 10$ pb^{-1} per week.
- Integrated lum ~ 200 pb^{-1} by July 2002.

Plan as of now (Feb 2002) :

- Peak lum of 1.1×10^{31} achieved thus far.
  Need to improve $\bar{p}$ transfer (MI to Tev) efficiency.
  Between now and July 2002:
  Integrated lum ~ 50 pb^{-1}.
- Still some physics results expected this summer.
- 300 pb^{-1} by end of 2002.
- 1200 pb^{-1} by end of 2003.
- 2500 pb^{-1} in Run IIa total (end of 2004).
- After that, Run IIb continues until 2008, 15 fb^{-1}.

$\sin 2\beta$ from $B^0/\bar{B}^0 \to J/\psi K_S^0$

Extrapolate yield from Run I

1988-89	Run 0	400	$J/\psi \to \mu^+\mu^-$ / pb^{-1}
1992-95	Run I	4000	$J/\psi \to \mu^+\mu^-$ / pb^{-1}
2001-03	Run II	15000	$J/\psi \to \mu^+\mu^-$ / pb^{-1}
		6000	$J/\psi \to e^+e^-$ / pb^{-1}

Track trigger now moved to level-1.
p_T threshold : $2.2 \to 1.5$ GeV/c.
Add dedicated di-electron trigger.
$\Rightarrow$ 28000 $J/\psi K_S^0$ in 2 fb^{-1} (Was 400 in 0.1 fb^{-1}).

Improved flavor tagging ϵD^2, from 6.3% to 9.1%.
Time-of-flight K-π separation.
Improved SVX tracking coverage for lepton/jet charge.

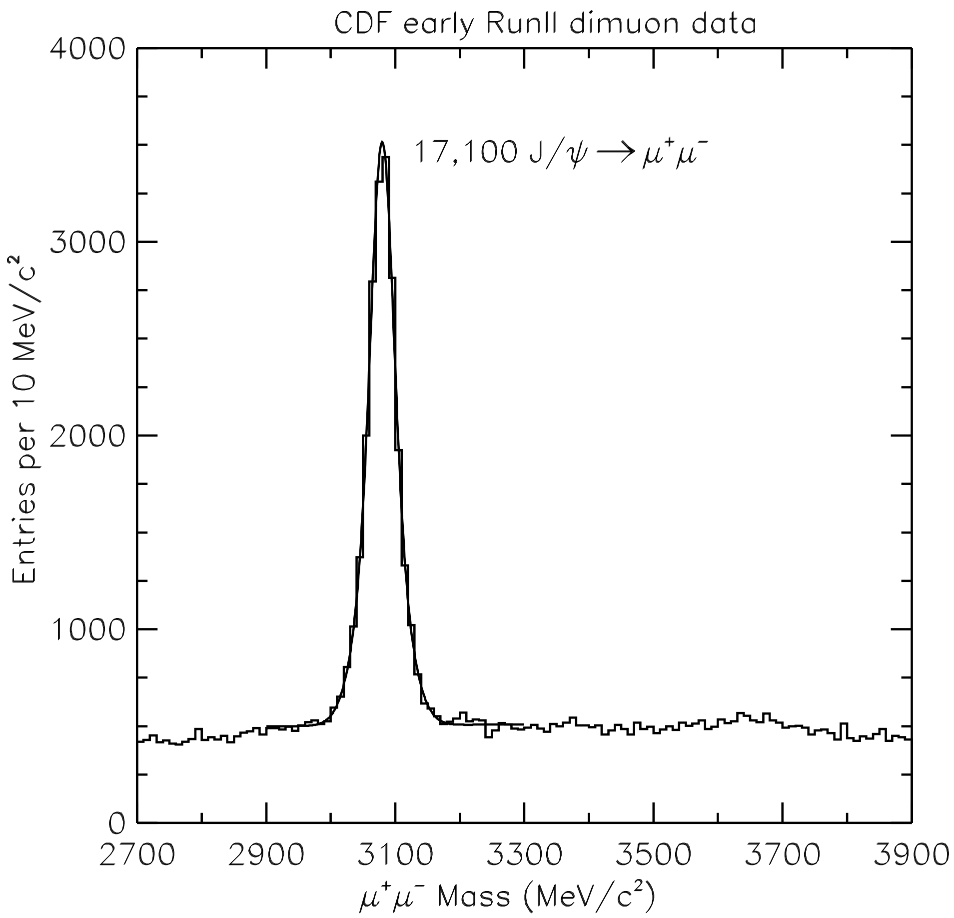
Scale statistical and systematic errors from Run I
Systematic = determination of flavor tag dilution
Used real data, $B^\pm \to J/\psi K^\pm$ and $B^0 \to J/\psi K^{*0}$.
Thus, scale with stat of calibration data samples.

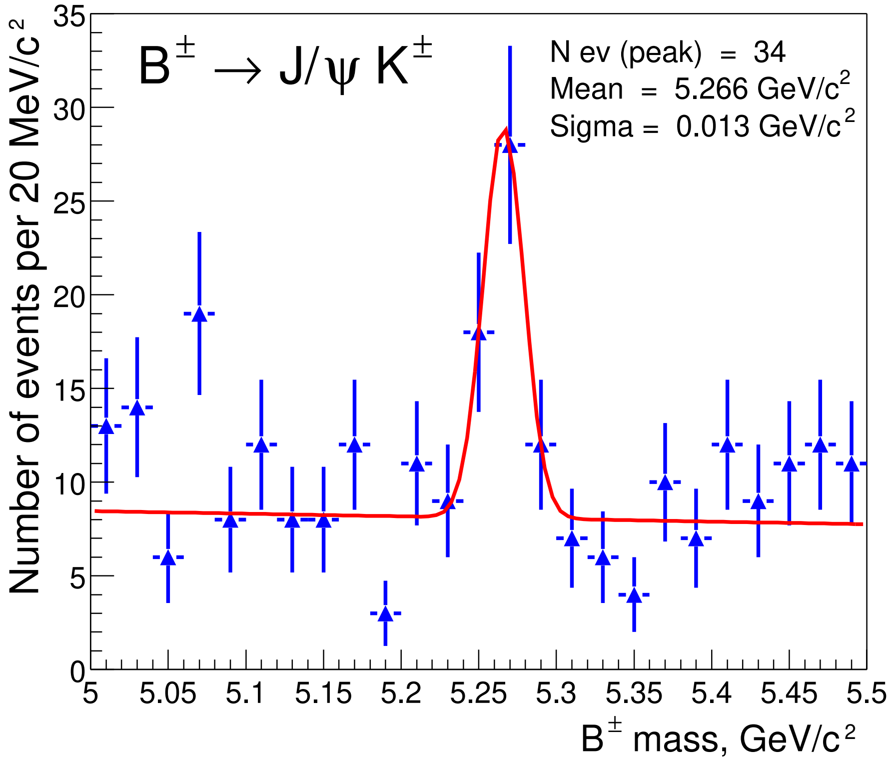
We expect

$$\sigma(\sin 2\beta) \simeq 0.043 \text{ with } 2\ \mathrm{fb}^{-1}.$$

cf: Belle/BaBar currently have uncertainty of ± 0.15 with about 30 fb^{-1} of data each.

Run-II Dimuon Data





Δm_s : $B_s^0 \bar{B}_s^0$ Oscillations

- $\Delta m_s / \Delta m_d \Rightarrow |V_{ts}/V_{td}|$ with less theory uncertainty.
- If SM fits are correct, it should be just around the corner:
$$15.4 < \Delta m_s < 20.3 \text{ ps}^{-1}.$$
- Experimental challenge: seeing very rapid oscillations.
  - Need $p(B_s^0)$ of each event to get proper time.
  - Difficult if missing particles exist, e.g. $\bar{B}_s^0 \to \ell^- \bar{\nu} D_s^+ X$.
  - Want full reconstruction $\bar{B}_s^0 \to D_s^+ \pi^-$, $D_s^+ \pi^+ \pi^- \pi^-$.
- Employ impact parameter track trigger (SVT) at level-2.

  Resolution $\sim 40\ \mu$m for $p_T > 2$ GeV/c.
- Expect 5000 to 30000 $\bar{B}_s^0 \to D_s^+ (n\pi)^-$ decays in 2 fb^{-1}.

  S/B: 1/2 to 2.

  $\sigma_t = 45 \oplus (\sigma_p/p)\, t$ fs ($\sim 14\ \mu$m).

  Flavor tagging: $\epsilon D^2 = 11\%$.

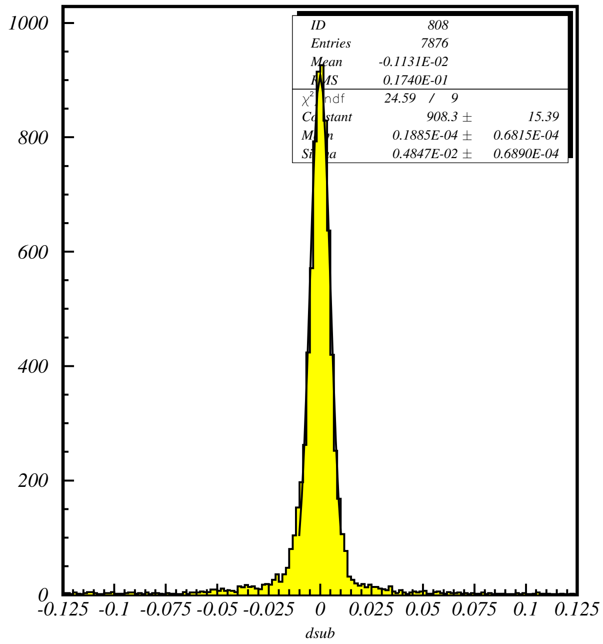
  Can observe Δm_s up to 40 ps^{-1} as a $> 5\,\sigma$ effect.

  Once seen, Δm_s will be determined to a few %.

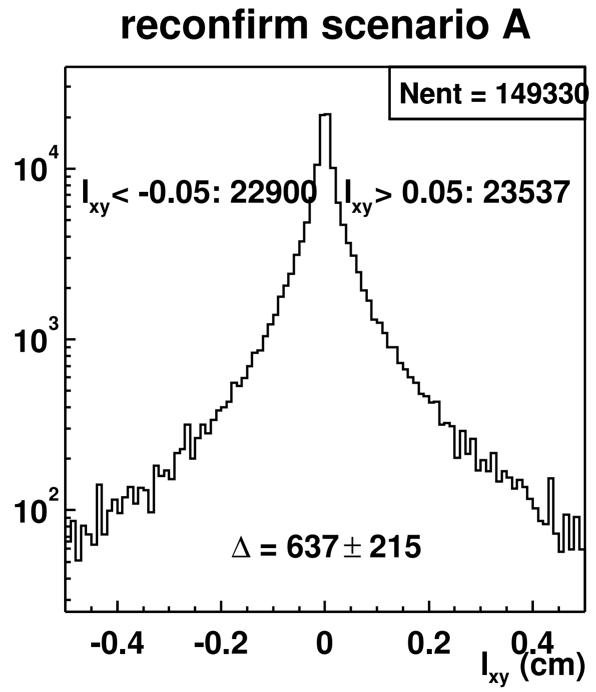
$\Rightarrow$ $|V_{td}/V_{ts}|$ also determined to a few %.

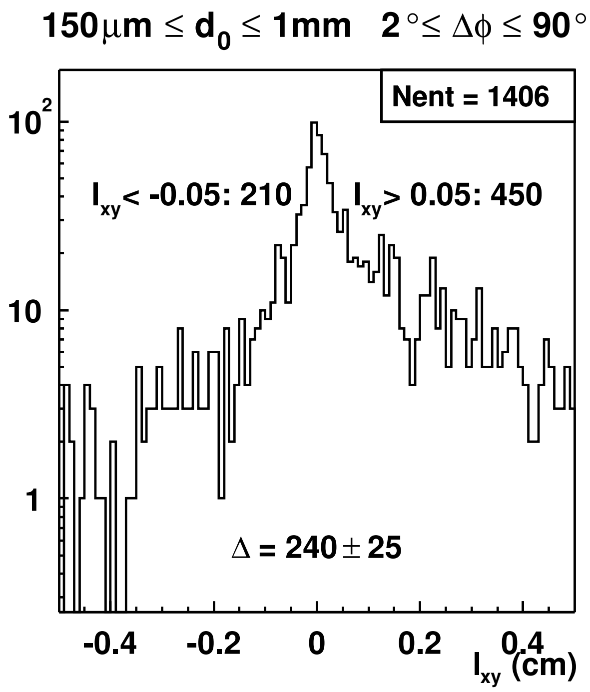
SVT: Silicon Vertex Trigger

Use silicon detector information at 2nd level trigger. Calculate track impact parameter d wrt beam spot.



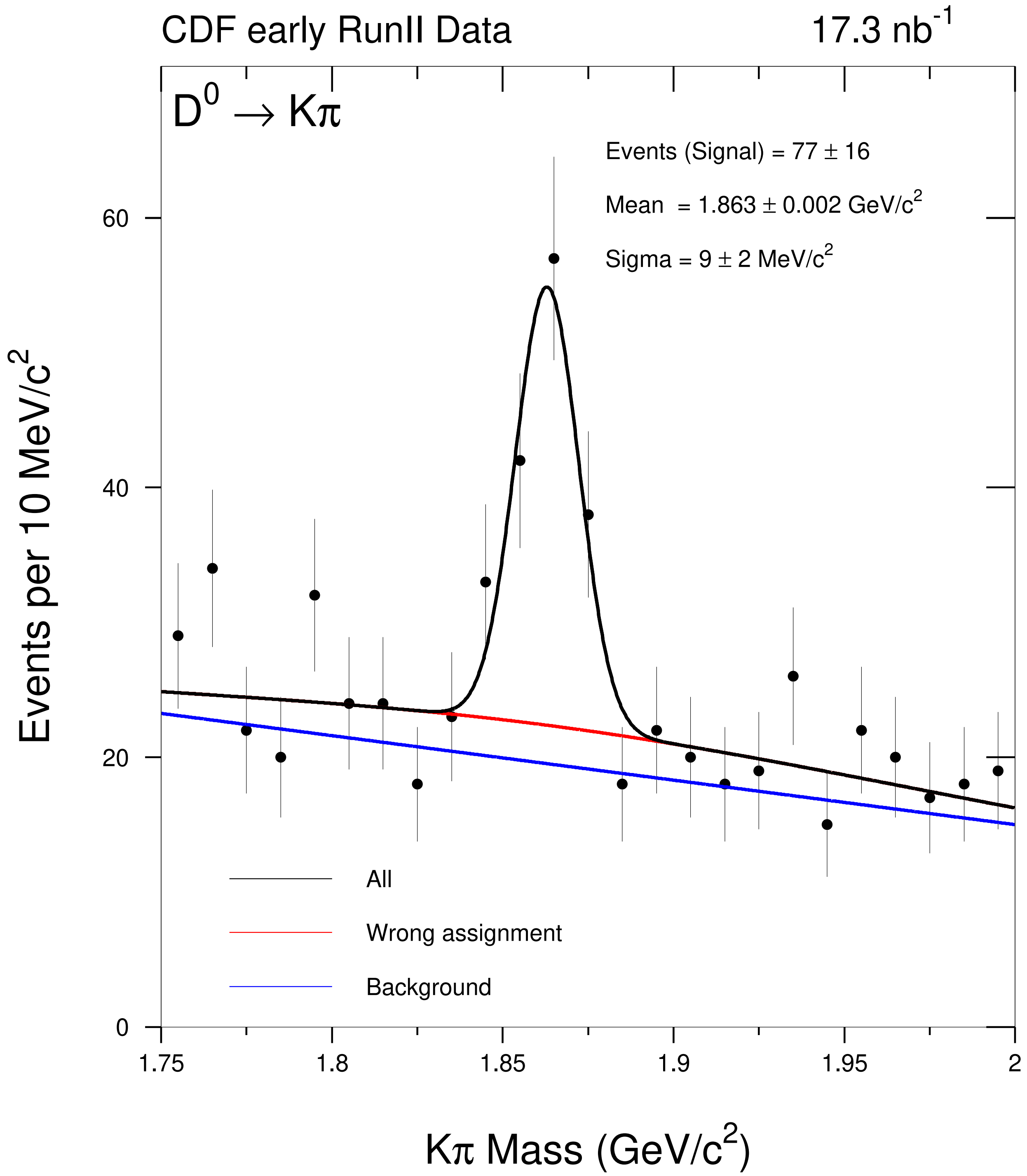
Cut on d, e.g. $|d| > 100\ \mu$m. Require two such tracks. Calculate decay length L_{xy}, require $L_{xy} > 500\ \mu$m.



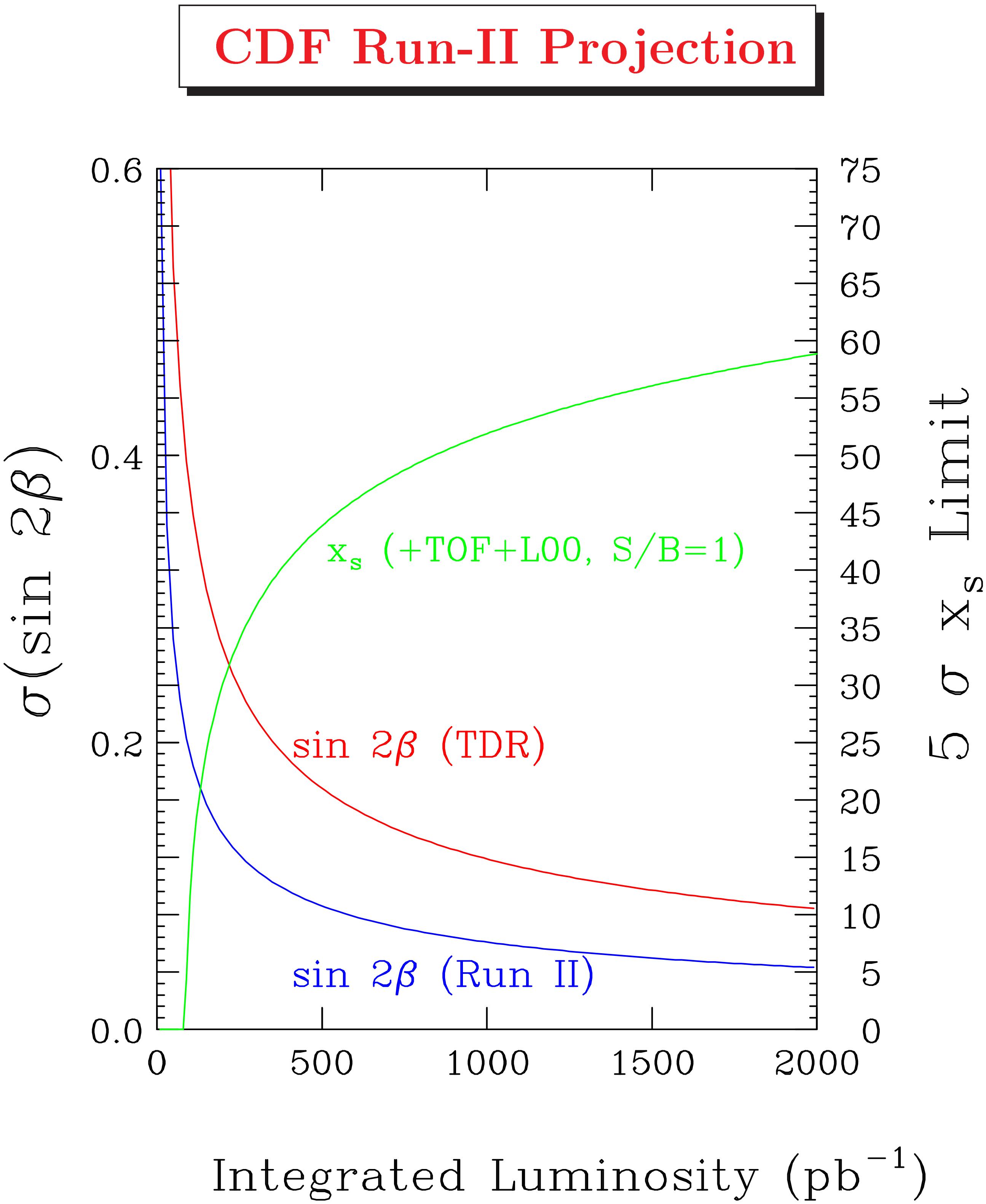


SVT: Silicon Vertex Trigger

$D^0 \to K^-\pi^+$ seen among a small amount of test data.



Next step: accumurate events, see $B \to D(n\pi)$.



Left axis: $\sin 2\beta$ precision.
Right axis: $B_s^0 \overline{B}_s^0$ oscillation discovery limit.

Angle γ : Phase of V_{ub}

Until a few years ago, $B^0/\overline{B}^0 \to \pi^+\pi^-$ was thought to be the mode for this (measured quantity is α), assuming $b \to u$ tree dominance over penguins.

- CLEO sees $\mathcal{B}(\overline{B}^0 \to K^-\pi^+) \gg \mathcal{B}(\overline{B}^0 \to \pi^+\pi^-)$, meaning penguis cannot be ignored.
- Penguins complicates business. Measured CP asymmetry is less cleanly related to angle α.
- Solutions proposed, but all experimentally challenging.

R. Fleischer : Throw in $B_s^0 \to K^+K^-$, take advantage of the penguin : Phys. Lett. B459, 306 (1999).

- Use $B^0 \to \pi^+\pi^-$ (tree > penguin)
  and $B_s^0 \to K^+K^-$ (tree < penguin)
- Tree and penguin interfere, so "direct" CP violation as well as mixing-induced CP violation:
  $\mathcal{A}^{\mathrm{CP}}(t) = \mathcal{A}^{\mathrm{DIR}} \cos \Delta m_d t + \mathcal{A}^{\mathrm{MIX}} \sin \Delta m_d t$
- Measure four $\mathcal{A}$'s from B^0 and B_s^0, then extract β, γ and tree and penguin decay amplitudes.
- B^0 and B_s^0 amplitudes related by U-spin ($d \to s$).

Angle γ continued

Four unknowns to extract :

- Angles γ and β
- d : ratio of penguin (P) to tree (T) ampliitudes, θ : phase of P/T.

$$d\,e^{i\theta} \equiv \frac{\lambda}{(1-\lambda^2/2)} \cdot \frac{|V_{cb}|}{|V_{ub}|} \cdot \frac{P}{T+P}$$

- d' and θ' for $B_s^0 \to K^+K^-$. $d' = d$ and $\theta' = \theta$ if U-spin symmetry is exact.

Four CP asymmetries to measure :

$$\begin{aligned}
\mathcal{A}^{\rm dir}(B^0 \to \pi^+\pi^-) &= \text{function}\,(\,d, \theta, \gamma) \\
\mathcal{A}^{\rm mix}(B^0 \to \pi^+\pi^-) &= \text{function}\,(\,d, \theta, \gamma, 2\arg(V_{td})) \\
\mathcal{A}^{\rm dir}(B_s^0 \to K^+K^-) &= \text{function}\,(\,d', \theta', \gamma) \\
\mathcal{A}^{\rm mix}(B_s^0 \to K^+K^-) &= \text{function}\,(\,d', \theta', \gamma, 2\arg(V_{ts}))
\end{aligned}$$

If no penguin, $\mathcal{A}^{\rm dir}(B^0, B_s^0) = 0$, $\mathcal{A}^{\rm mix}(B^0) = \sin 2(\beta+\gamma)$, $\mathcal{A}^{\rm mix}(B_s^0) = \sin 2\gamma$.

By the time we do this, we should know β precisely. Then fit for γ, d, θ.

Expect $\sim$ 5 k $B^0 \to \pi^+\pi^-$ and $\sim$ 10 k $B_s^0 \to K^+K^-$ events in 2 fb^{-1}.
$\Rightarrow$ angle γ to $\sim \pm 10^\circ$.

Other Topics

- **Search for CP-violation in $B_s^0/\bar{B}_s^0 \to J/\psi\phi$**
  A_{CP} to $\sim \pm 0.1$. Expect ~ 0 in SM, new physics if substantial.
- **Width difference $\Delta\Gamma$ in $B_s^0\bar{B}_s^0$ system**
  Potential for CP studies with untagged B_s^0 decays.
  $\sigma(\Delta\Gamma/\Gamma) \simeq 0.024$ from $J/\psi\phi$ vs. $D_s^+\pi^-$.
  Also, direct check with $D_s^{(*)+}D_s^{(*)-}$.
- **Rare decays:**
  $B \to \mu^+\mu^- K^{(*)}$, ~ 60 events in 2 fb^{-1}.
  Need more data for forward/backward asymmetry.
  Also $(B^0 \to K^{*0}\gamma)$ / $(B^0 \to \rho^0\gamma)$
  and $(B_s^0 \to \phi\gamma)$ / $(B_s^0 \to K^{*0}\gamma) \Rightarrow |V_{ts}/V_{td}|$.
- **Angle γ from $B_s^0 \to D_s^{\mp}K^{\pm}$?**
  Theoretically clean, but BG from $D_s^-\pi^+$ tough.
  Hope to see signal in 2 fb^{-1}.
- **Precision lifetime ratios : B_s^0/B^0, B_c^+/B^0, Λ_b/B^0**
- **Full reconstruction of $B_c^+ \to J/\psi\pi^+$, $B_s^0\pi^+$ ...**
- **QCD b and c production, onium polarization.**

Much of them pretty complementary to $\Upsilon(4S)$.

Summary : 2 fb^{-1} (2004)

- Major upgrades complete for Run-II CDF. Has just started taking data.

  Vastly improved B physics potential :

  Integrated luminosity $\times 20$ in 2004.

  CDF : better vertexing, impact parameter track trigger.

- Two major measurements of the CKM triangle, perhaps well before 2 fb^{-1}.

  $\sin 2\beta$ to ± 0.043.

  Δm_s up to 40 ps^{-1} (expect ~ 17 ps^{-1} in SM).

- Some optimism for third major measurement.

  Angle γ to $\sim 10°$ from $B^0 \to \pi^+\pi^-$ plus $B_s^0 \to K^+K^-$
  (modulo SU(3) breaking effects).

- B_s^0 measurements unique to CDF, and play important roles.

- Many other measurements expected.

  Some benefit from (or require) more than 2 fb^{-1}.
  Expect 15 fb^{-1} by the end of 2008.

- Then we quit. BTeV starts next.

Short Term Goals : 50 pb^{-1} this summer

- $J/\psi \rightarrow \mu^+\mu^-/e^+e^-$ trigger :

  600,000 J/ψ's (15% from B decays)

  Exclusive B signals, e.g. 400 $B^0 \rightarrow J/\psi\, K^0_S$

- Two-track SVT trigger :

  $D^0 \rightarrow K^-\pi^+ = 600,000$ ($\bar{p}p \rightarrow c\bar{c}X,\ b\bar{b}X$)

  $B^0 \rightarrow K^+\pi^-/\pi^+\pi^- = 500$

  $\bar{B}^0_s \rightarrow D^+_s\pi^- = 240$

  Examine feasibility of $B^0 \rightarrow \pi^+\pi^-$

- Lepton + SVT displaced track trigger :

  $\bar{B}^0_s \rightarrow \ell^-\bar{\nu}D^+_sX = 700.$

  $b \rightarrow \ell^-X = 500,000$

  Use sample to optimize flavor tagging ϵD^2.

- Establish and optimize flavor tagging.

  Finding signal is “easy”, flavor tag is tough.

  Crucial to get large ϵD^2 for CP, mixing.

  Get ready for $\sin 2\beta$ and Δm_s.

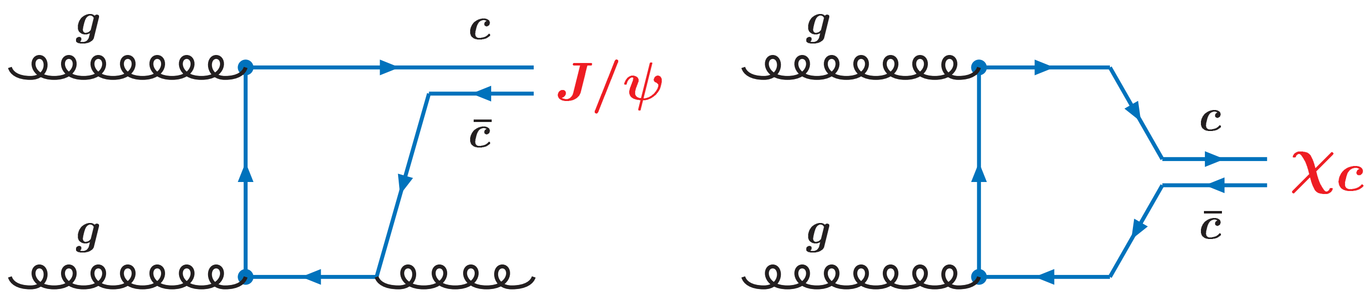
Quarkonium Production

Quarkonia: bound states of heavy quark Q and its antiquark $\bar{Q}$.

$c\bar{c}$ states :
$L = 0,\ S = 0,\ J^P = 0^-$: η_c
$L = 0,\ S = 1,\ J^P = 1^-$: $J/\psi,\ \psi(2S), \ldots$
$L = 1,\ S = 1,\ J^P = 0^+,\ 1^+,\ 2^+$: $\chi_{c0},\ \chi_{c1},\ \chi_{c2}$

Similarly for $b\bar{b}$:
$L = 0,\ S = 0,\ J^P = 0^-$: η_b
$L = 0,\ S = 1,\ J^P = 1^-$: Υ
$L = 1,\ S = 1,\ J^P = 0^+,\ 1^+,\ 2^+$: $\chi_{b0},\ \chi_{b1},\ \chi_{b2}$

$J/\psi \to 3g$, $\chi_{c(0,2)} \to 2g$.



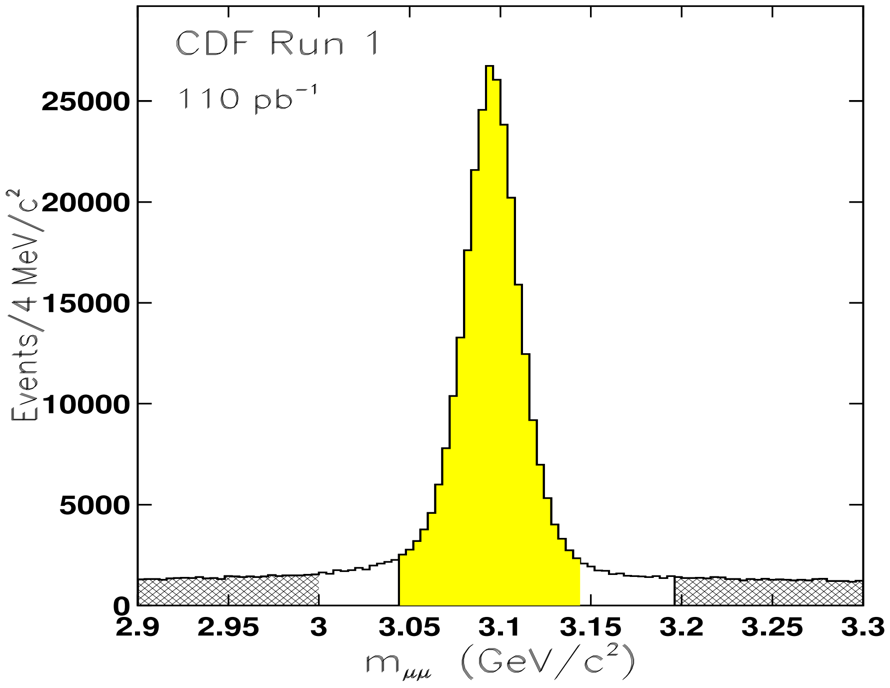
"Old" theory had predicted :

$$\sigma(\,\psi(2S),\ \text{direct } J/\psi\,) \ll \sigma(\chi_c).$$

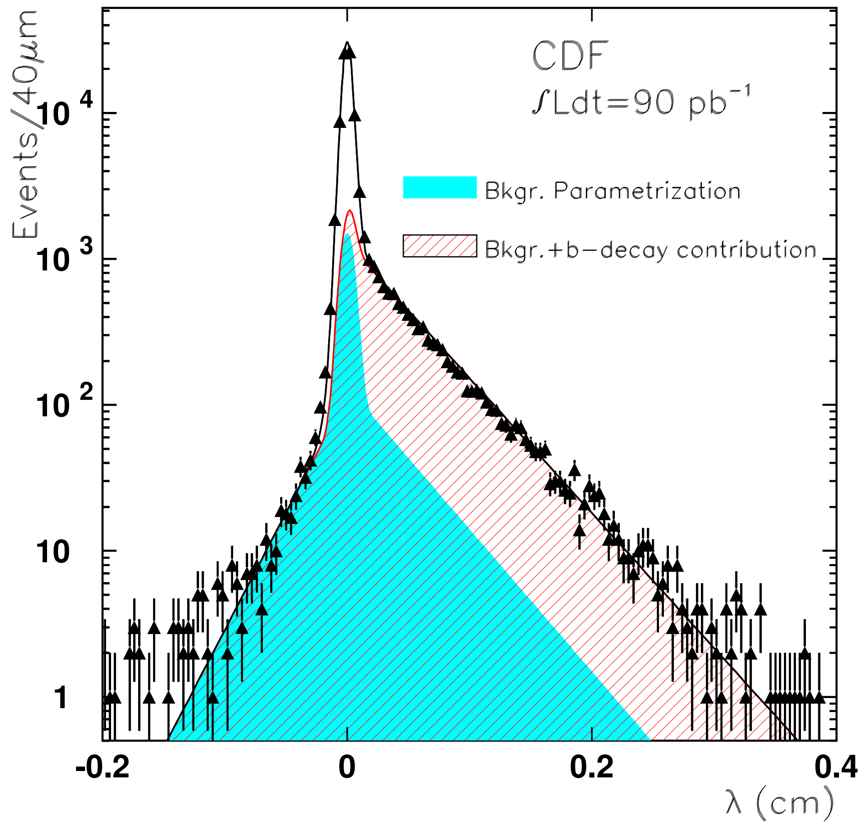
"Direct" $\equiv$ Not from χ_c, $\psi(2S)$ or B.

CDF has found $\times 50$ direct J/ψ and $\psi(2S)$ yields than "color singlet model".

$J/\psi \to \mu^+\mu^-$ **signal :** $\sim$ **250 k in 110 pb**$^{-1}$



Decay length distribution



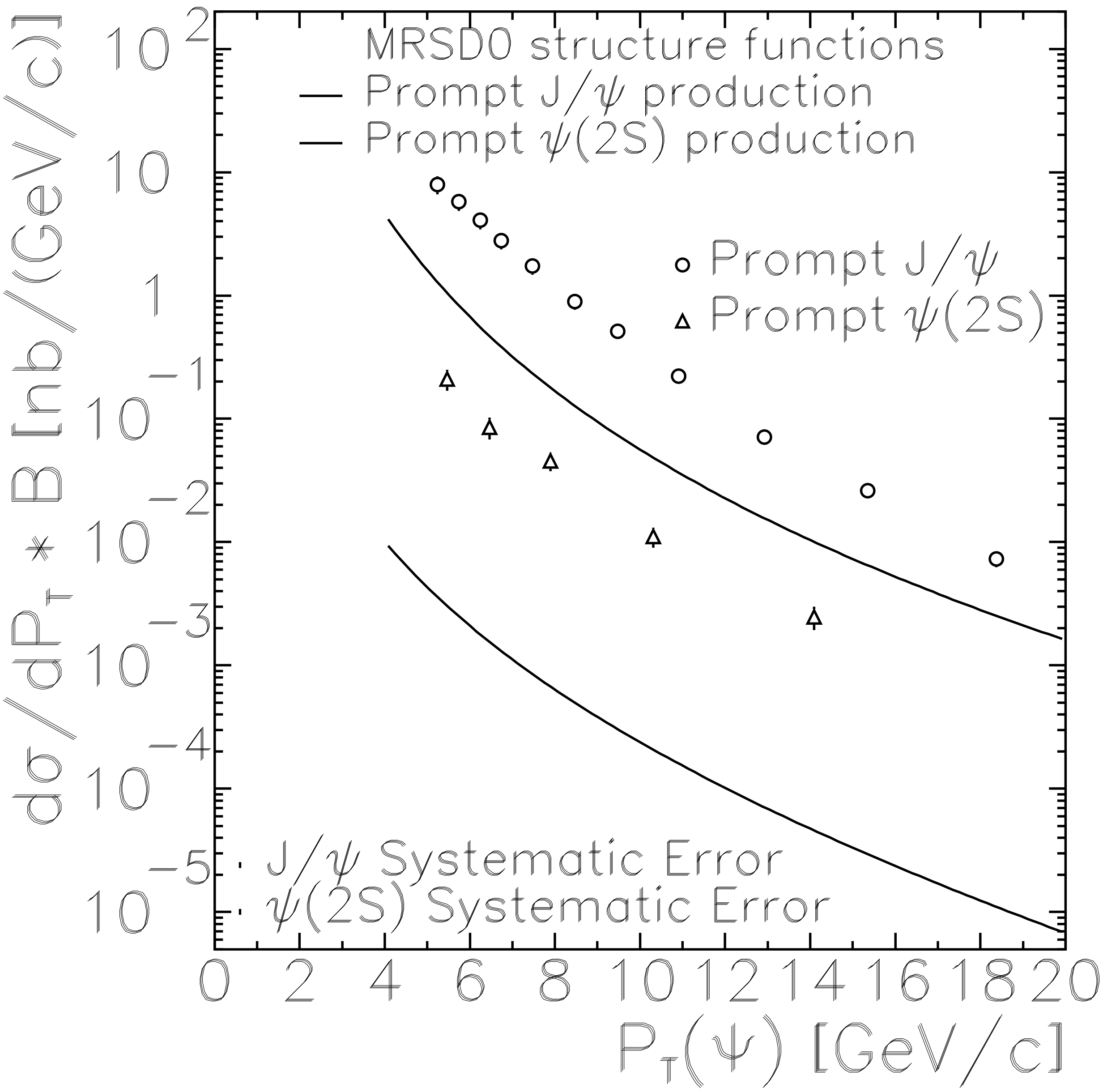
$\sim$ **20% of** J/ψ**'s from** B **decays.**
Rest has zero lifetime : "prompt".

J/ψ and $\psi(2S)$ Production

Sources :

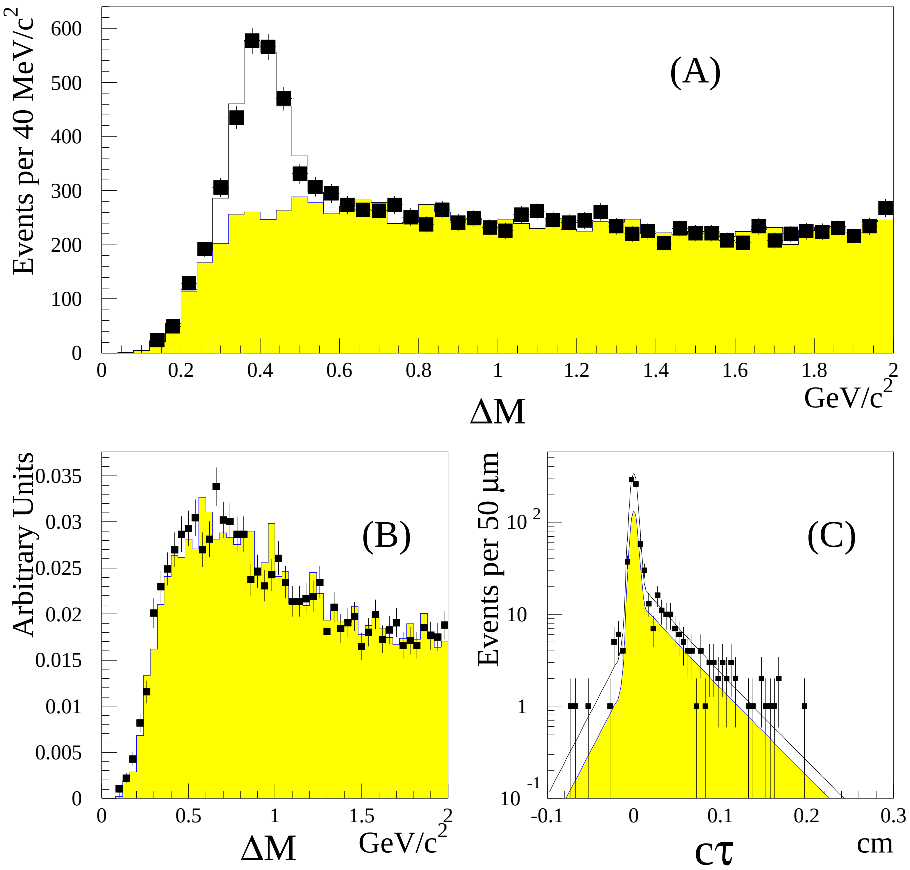
- $B \to J/\psi X$ **(lifetime,** $\sim$ **20% of all)**
- **Direct** J/ψ
- **Direct** $\chi_c \to J/\psi\,\gamma$ **(not the case for** $\psi(2S)$**)**

The latter two have zero lifetime ("prompt") :

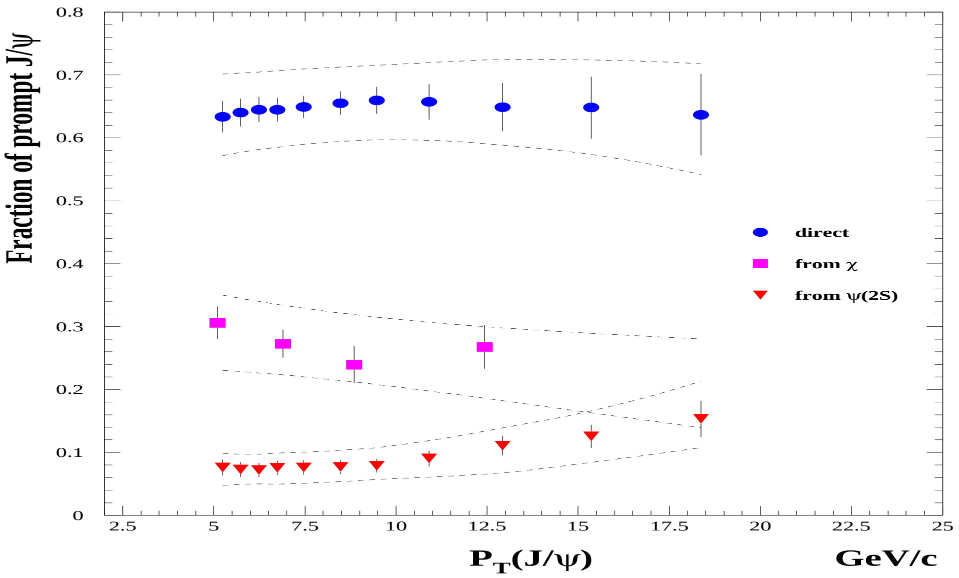


J/ψ from χ_c : $\chi_c \to J/\psi\,\gamma$

Identify γ with CEM/CES, combine it with J/ψ, calculate $\Delta M \equiv M(J/\psi\,\gamma) - M(J/\psi)$.



Use lifetime to subtract $B \to \chi_c X$.
Then extract sources of <u>prompt</u> J/ψ's.

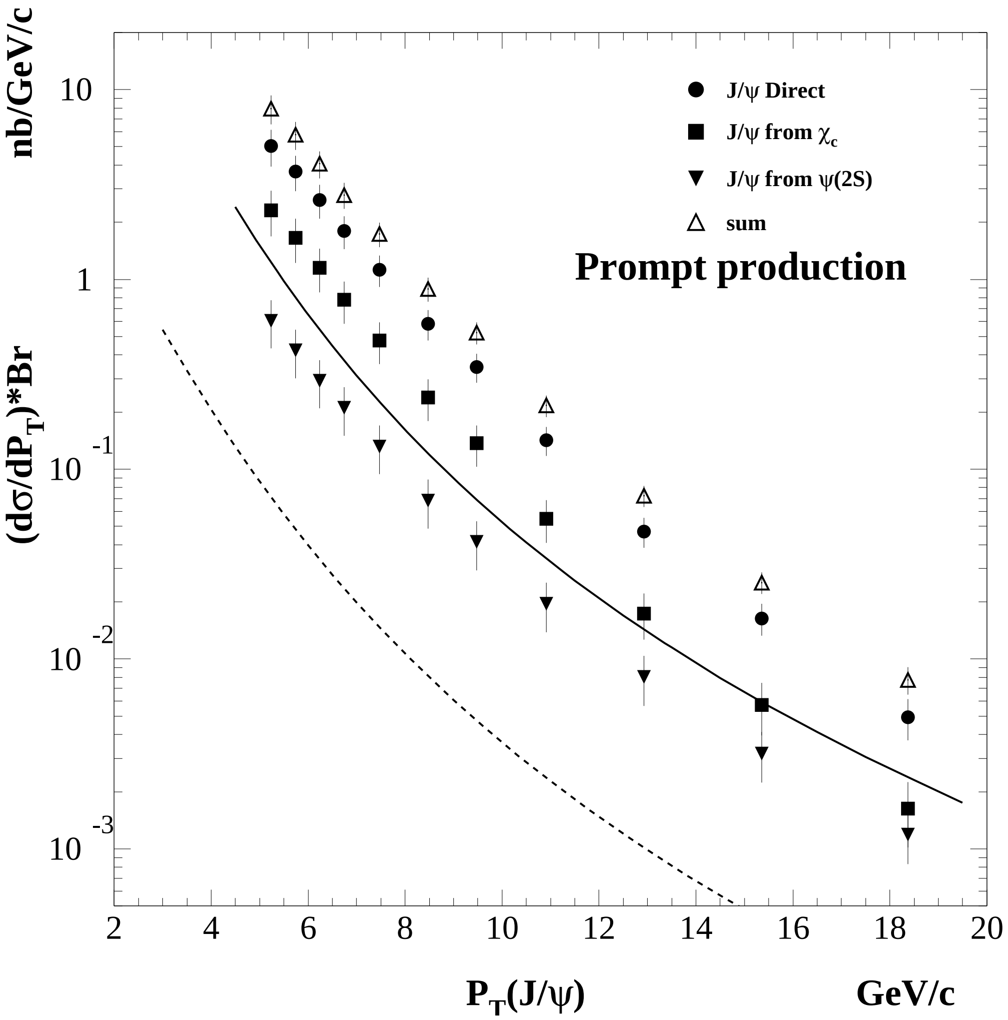


direct

from χ_c

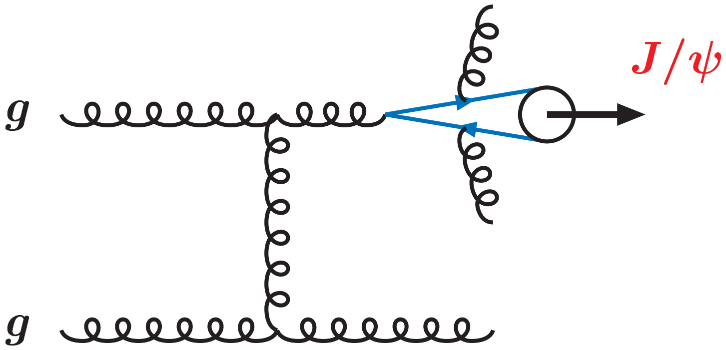
from $\psi(2S)$

Prompt J/ψ Production Breakdown



Direct production: both J/ψ and $\psi(2S)$ higher than prediction by a factor of ~ 50.

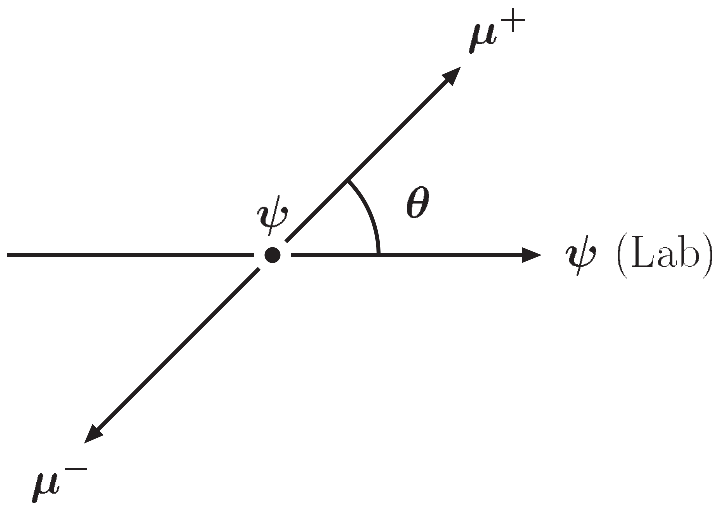
Other mechanisms must exist.
Gluon fragmentation?
Color octet?



J/ψ and $\psi(2S)$ Polarization

Gluon fragmentation into ψ :

Gluons are massless ($p_T \gg m_\psi$) and thus transversely polarized.
ψ should inherit the gluon polarization.
Helicity angle:



$$\frac{dN}{d\cos\theta} = 1 + \alpha\cos^2\theta$$

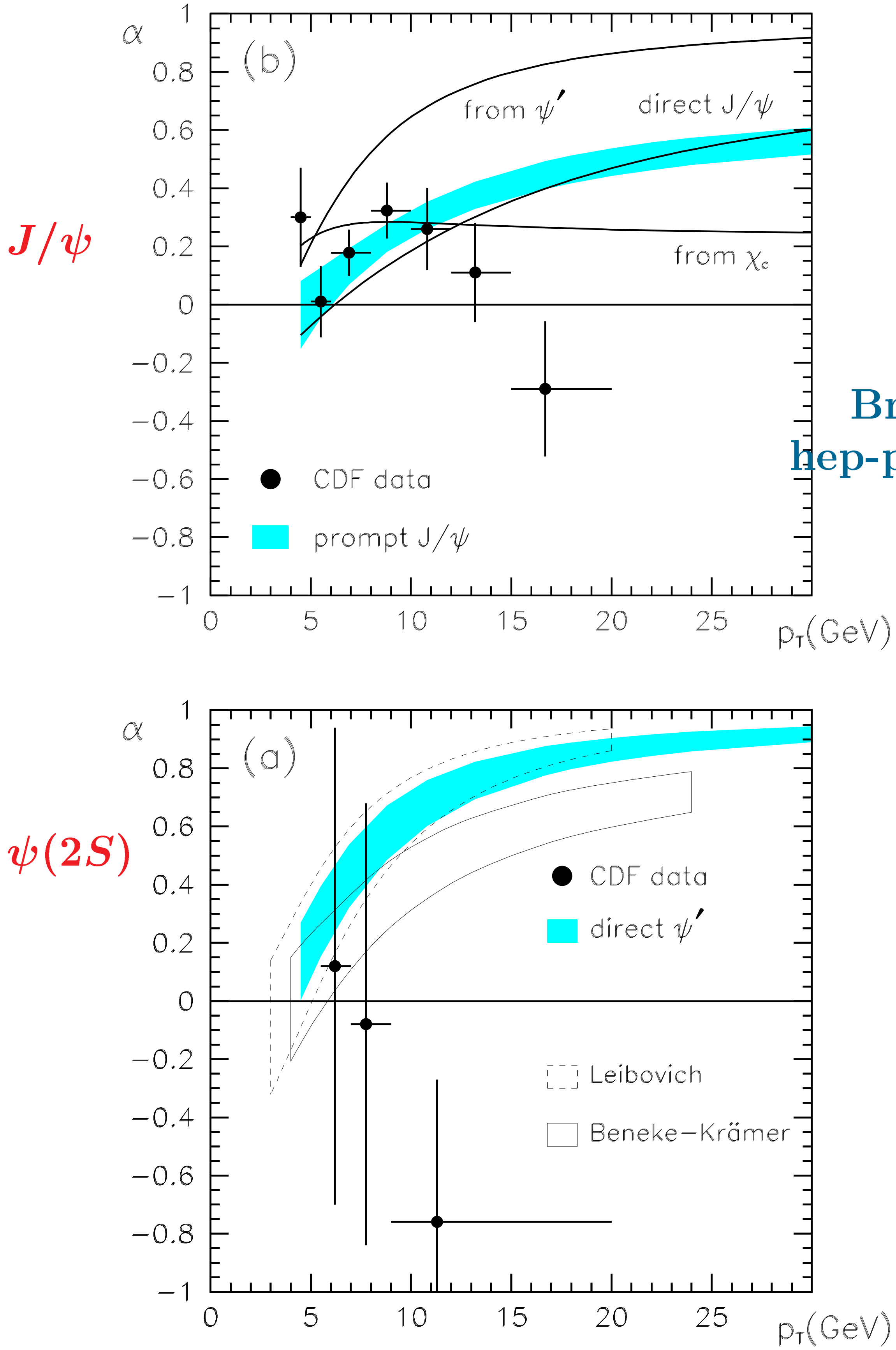
$\alpha = +1 \Rightarrow$ 100% transverse.
$\alpha = -1 \Rightarrow$ 100% longitudinal.

Prediction for direct production

Beneke and Krämer	$\alpha = 0.77 \pm 0.08$
Leibovich	$\alpha = 0.90 \pm 0.04$

at $p_T = 20$ GeV/c.

J/ψ and $\psi(2S)$ Polarization

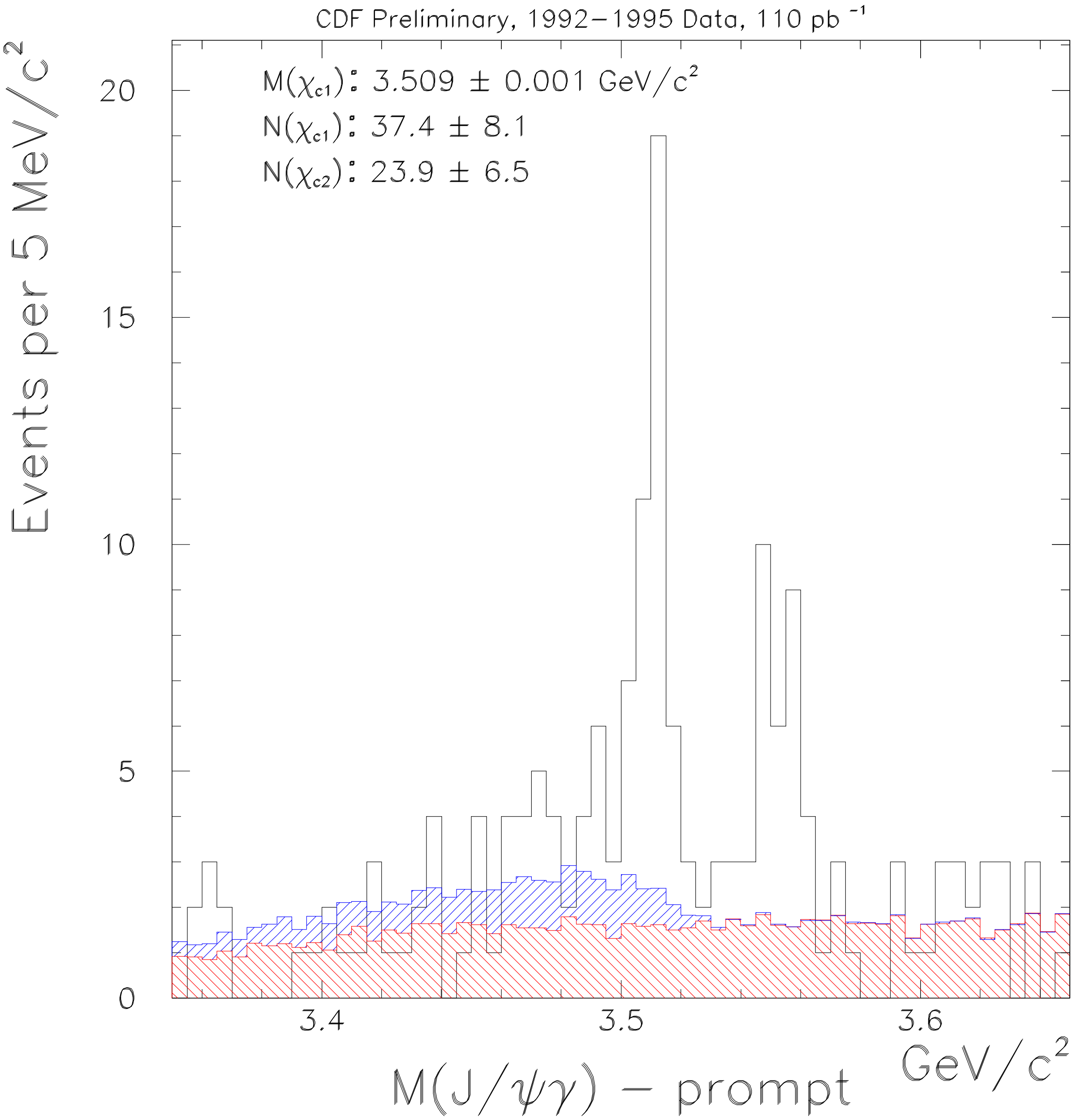


Theory:
Braaten *et al.*
hep-ph/9911436

Phys. Rev. Lett. 85, 2886 (2000).

χ_c Production : separate χ_{c1} and χ_{c2}.

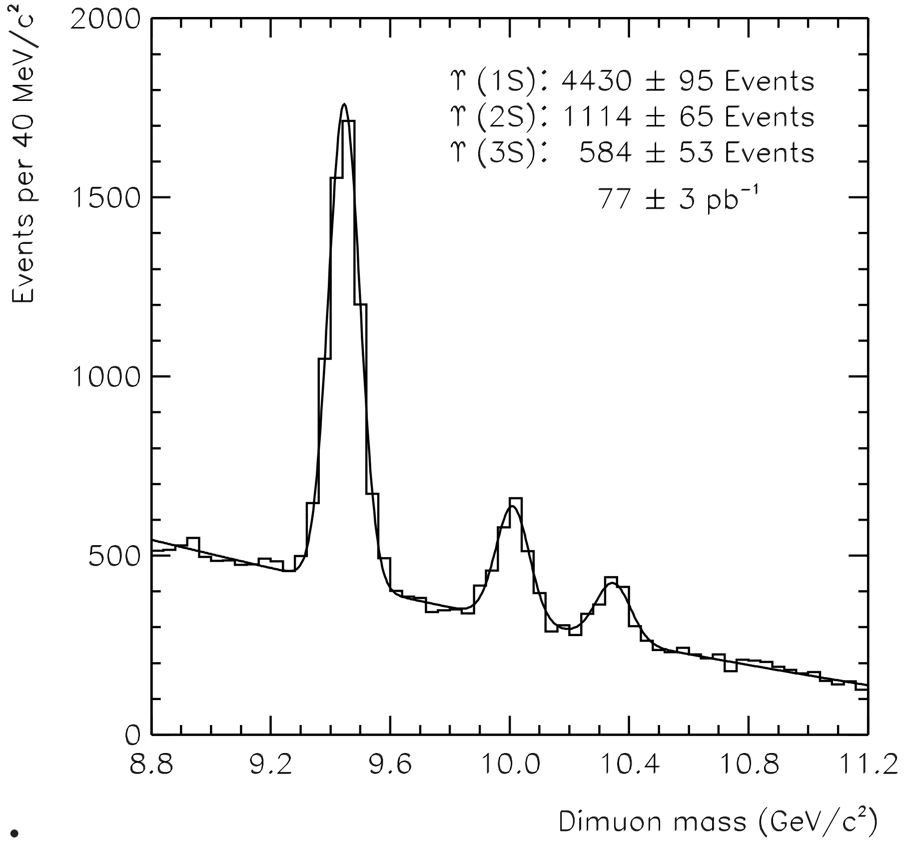
Need good energy resolution for photon :
$\Rightarrow$ use converted $\gamma \rightarrow e^+e^-$ (tracking momentum resolution better than calorimeter)



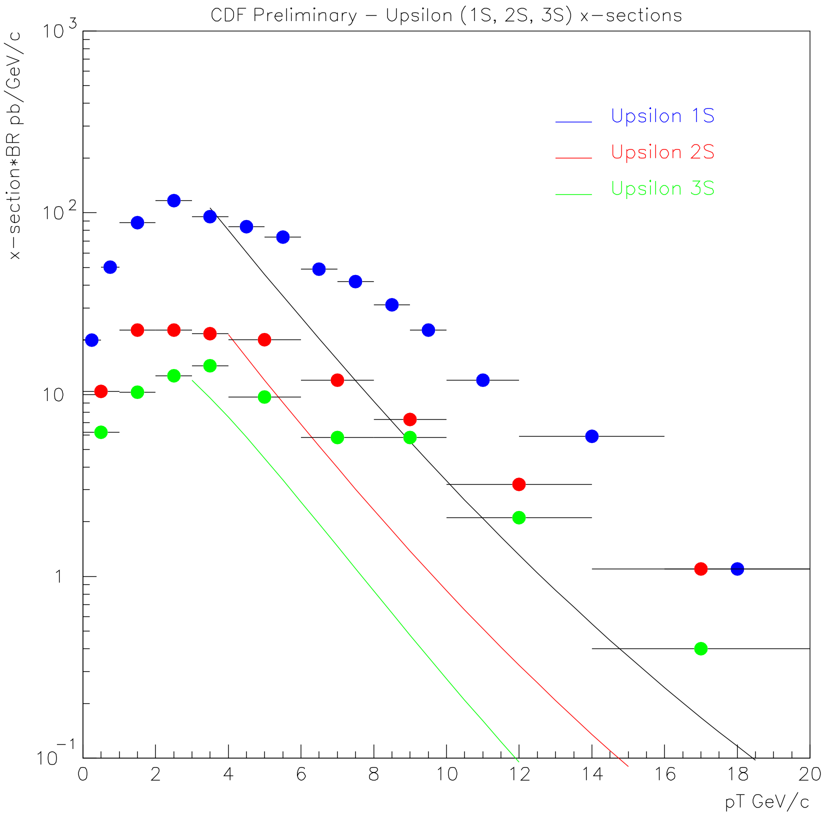
$$\frac{\boldsymbol{\sigma}(\chi_{c2})}{\boldsymbol{\sigma}(\chi_{c1})} = \mathbf{0.89 \pm 0.33}\,^{+0.13}_{-0.10}$$

Υ Production

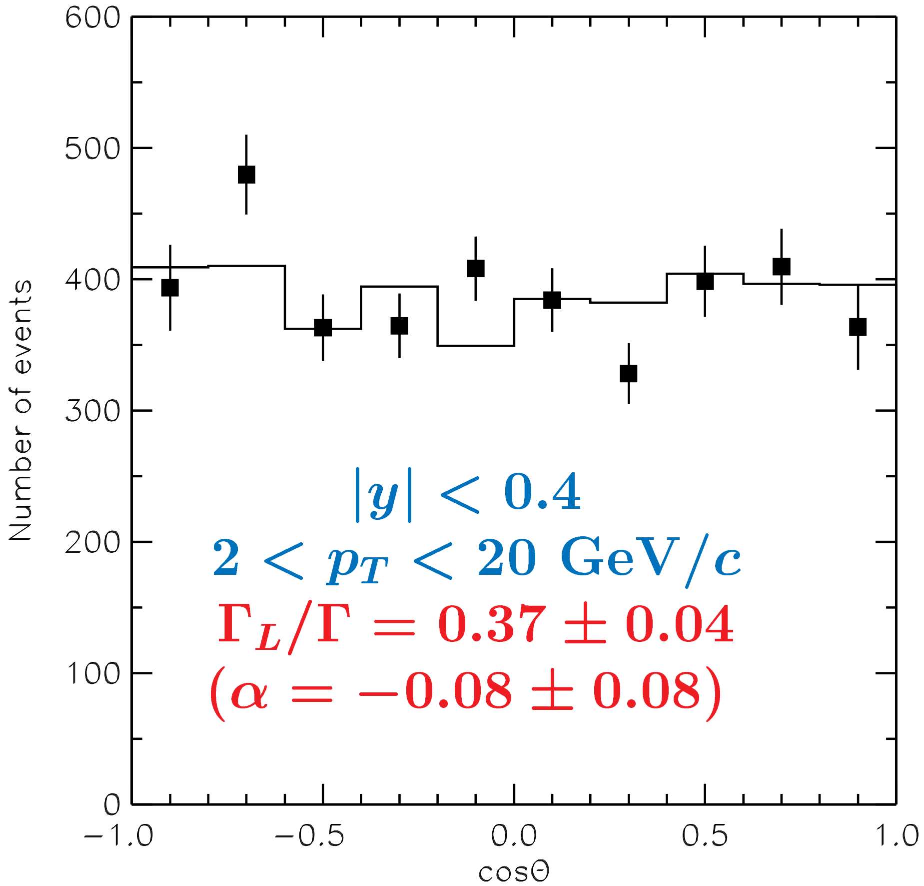
Mass peaks



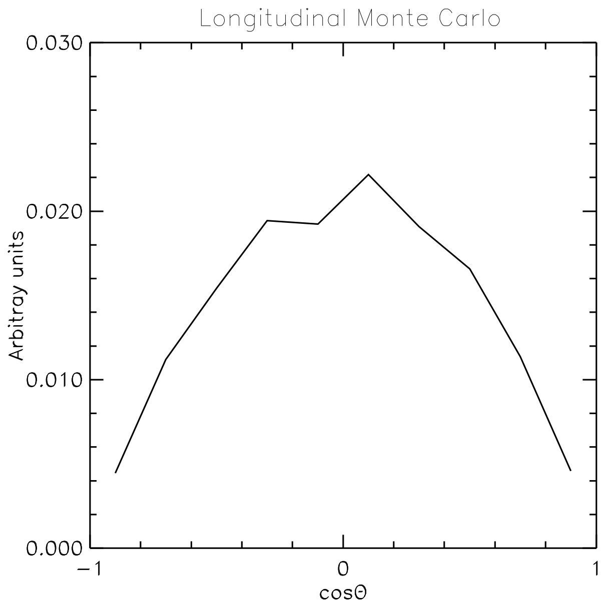
Cross section vs. p_T



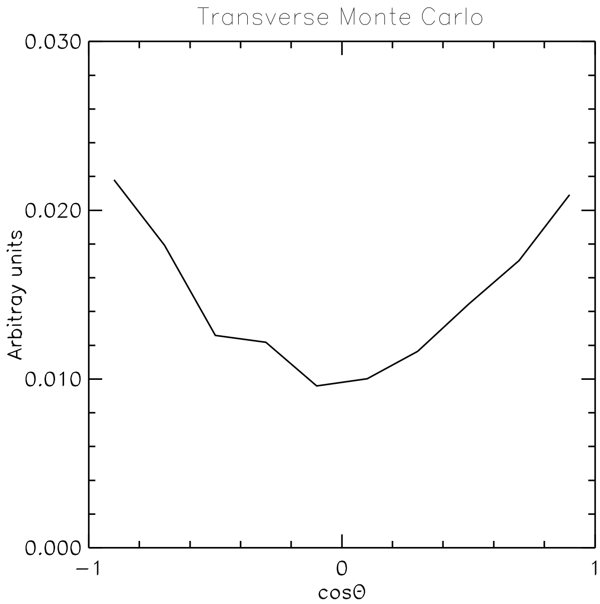
$\Upsilon(1S)$ Polarization



Templates :



Longitudinal



Transverse

Sub. to PRL (Fermilab-Pub-01/355-E)