8.882 LHC Physics

Experimental Methods and Measurements

Onia as Probes in Heavy Ion Physics
[Lecture 10, March 9, 2009]

Lecture Outline

Onia as Probes in Heavy Ion Physics

- what are onia? and bit of history
- why are they interesting in heavy ion physics?
- what can we do with them in High Energy physics?
- production and their decay
- general reconstruction of onia

Positronium Started it All

Positronium

(lives ≈100 ns, discovered 1951 by Martin Deutsch, MIT)

- quasi stable system of electron and positron (exotic atom)
- decays to *n* photons (more than 1, spin argument 2 *vs* 3)
- compares closely to hydrogen atom: energy levels (Bohr)

$$E_n = \frac{-m^* q_e^4}{8 h^2 \varepsilon_0^2} \frac{1}{n^2}$$

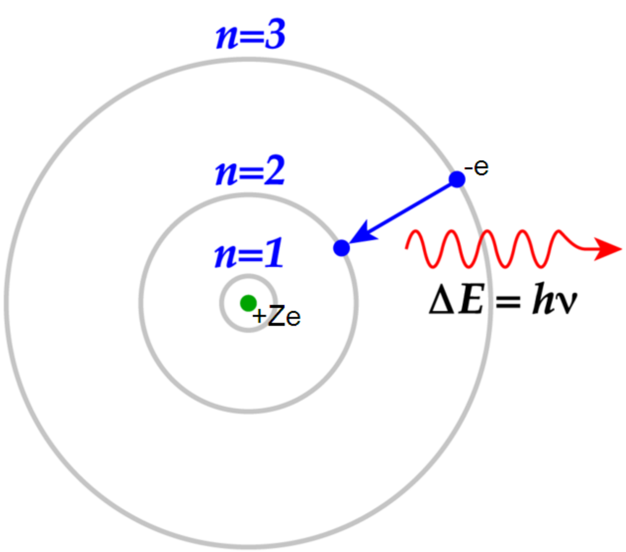
h – Planck's constant
ε_0 – electric constant
q_e – electron charge

- difference to hydrogen: reduced mass (m^*)

$$m^* = \frac{m_e m_p}{m_e + m_p} = \frac{m_e}{2}$$

- plugging in the numbers we find

$$E_n = \frac{-m_e q_e^4}{16 h^2 \varepsilon_0^2} \frac{1}{n^2} = \frac{-6.8\ \text{eV}}{n^2}$$



Charge Shielding in Plasma

Debye length

- defines distance over which mobile charge carriers shield out electric fields in a plasma (for colder ions)

$$\lambda_D = \sqrt{\frac{\varepsilon_0 k T_e}{n_e q_e^2}}$$

T_e – electron temperature
ε_0 – permittivity of free space
n_e – electron density

Charge becomes invisible to outside

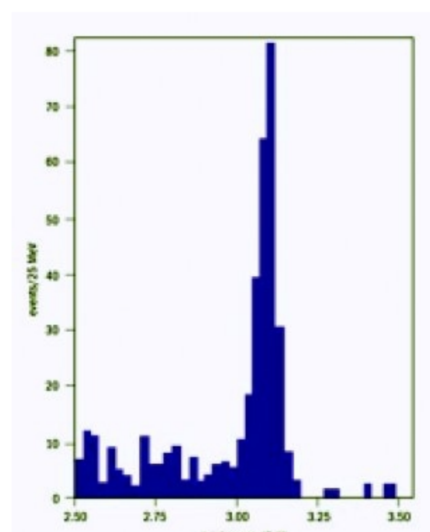
- positronium is nothing but a dipole
- charge screening should affect positronium in a plasma
- modified energy levels (high energy levels disappear first)
- for high enough densities it should even disappear all together

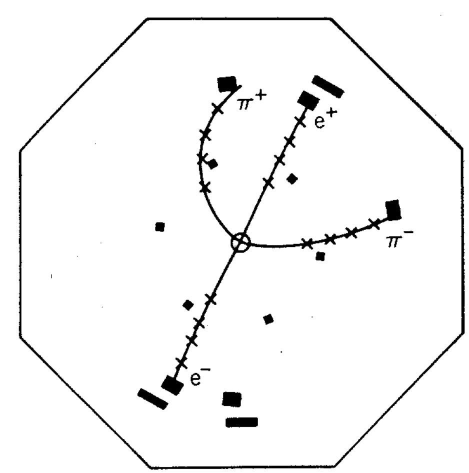
(Quark)Onia

Flavorless meson: quark and its own antiquark

- only heavy quarks (*c, b, (t))* are relevant, because light quarks all mix together because of similar masses
- charmonia: *J/Ψ, Ψ', Ψ'' etc.* are from: $c\bar{c}$
  - *J* – Brookhaven fixed target experiment (S.C.C. Ting, MIT)
  - *Ψ* – SLAC e^+e^- experiment (B. Richter, SLAC)
  - November Revolution: 1974, Nobel prize 1976
  - lifetime: 0.72 x 10^{-20} secs

Sam Ting describes his team's discovery of the new particle at Brookhaven to a packed auditorium at CERN.

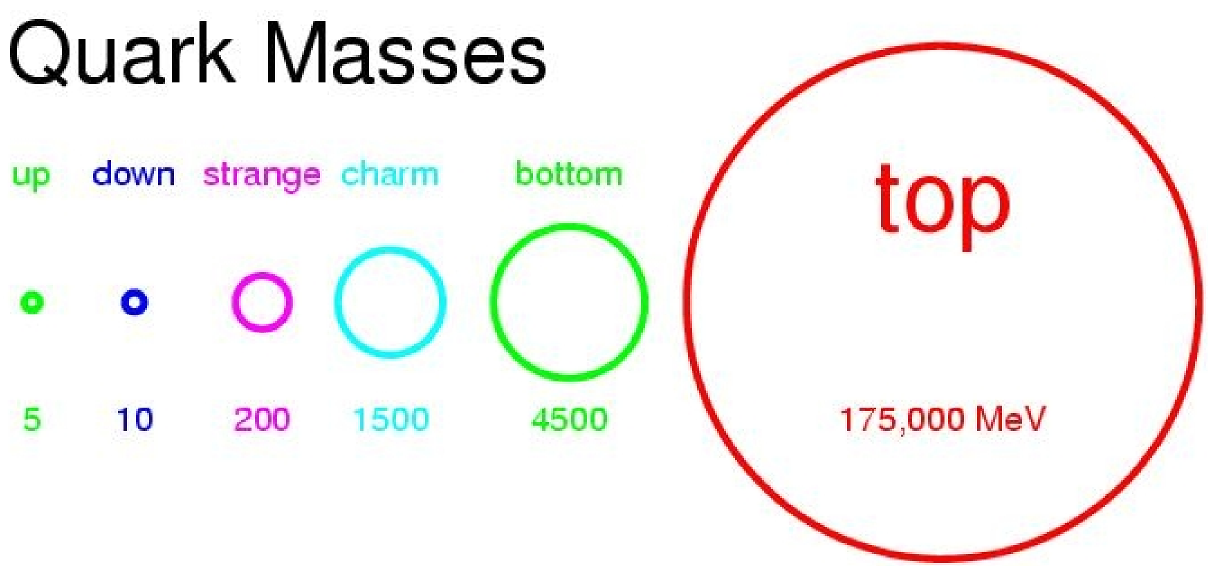


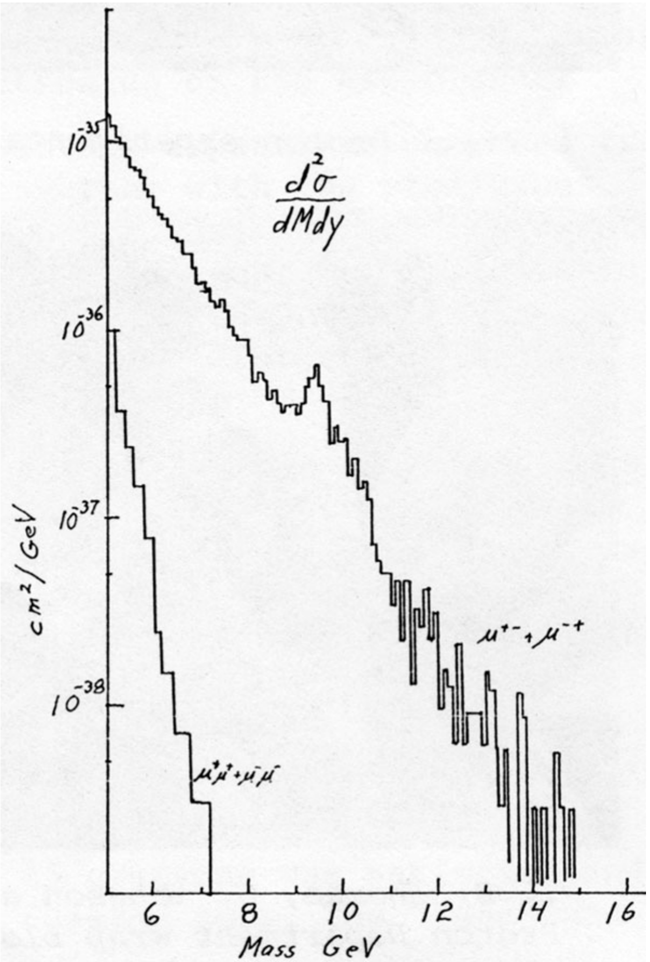


(Quark)Onia

Flavorless meson: quark and its own antiquark

- bottomonia: *Upsilon*(1S, 2S, 3S, 4S) *etc.* are from: $b\bar{b}$
  - *Upsilon* – E288 FNAL experiment (L. Lederman, Columbia)
  - discovered in 1977
  - lifetime: 1.21 x 10^{-20} secs
- toponium doesn't exist, too short lived





Theory of Onia

Theory predicts properties of Onia

- most importantly the masses
- very difficult because it is the typical example for the non-perturbative regime of QCD
- next order might be larger then the preceding one
- only general method (first principles) is lattice gauge theory
- speed of heavy quarks in onia small (0.3c for charmonia, and 0.1c for bottomonia)
- expand is orders of β and use for lattice (Non Relativistic QCD = NRQCD)
- some approximate theories work surprisingly well though
- effective potentials

Effective Theory of Quarkonia

Use non relativistic potential theory (not exact)

- Schroedinger equation:

$$\left(2m_c - \frac{1}{m_c}\nabla^2 + V(r)\right)\phi_i(r) = m_i\phi_i(r)$$

- Cornell potential:

$$V(r) = \frac{a}{r} + br$$

Coulomb potential, coupling, $a \approx \pi/12$

confining string tension: $b \approx 0.2\ \mathrm{GeV}^2$

Quarkonia masses, m_i, and radii, r_i

Account of Quarkonia Masses

Summary from potential models*

state	J/ψ	χ_c	ψ'	Υ	χ_b	Υ'	χ_b'	Υ''
mass [GeV]	**3.10**	**3.53**	**3.68**	**9.46**	**9.99**	**10.02**	**10.26**	**10.36**
ΔE [GeV]	**0.64**	**0.20**	**0.05**	**1.10**	**0.67**	**0.54**	**0.31**	**0.20**
ΔM [GeV]	**0.02**	**-0.03**	**0.03**	**0.06**	**-0.06**	**-0.06**	**-0.08**	**-0.07**
radius [fm]	**0.25**	**0.36**	**0.45**	**0.14**	**0.22**	**0.28**	**0.34**	**0.39**

NB: error in mass determination ΔM is less than 1 %

ΔE – binding energy

ΔM – mass difference observed with prediction

* lifted from talk by Hans Satz at http://hp2006.lbl.gov/source/program.htm

Relevance of Onia in HEP and HI

Onia in High Energy Physics

- defined new era of HEP
  - quark constellation formed around *J/Ψ, 1974 (u,d,s to [u,d], [c,s])*
  - family model emerged
- discovery of the third family, 1977 ([t,b]) with the *Upsilon*
- started long search for the top quark (TeVatron 1994)
- onia production and spectroscopy (NPQCD)

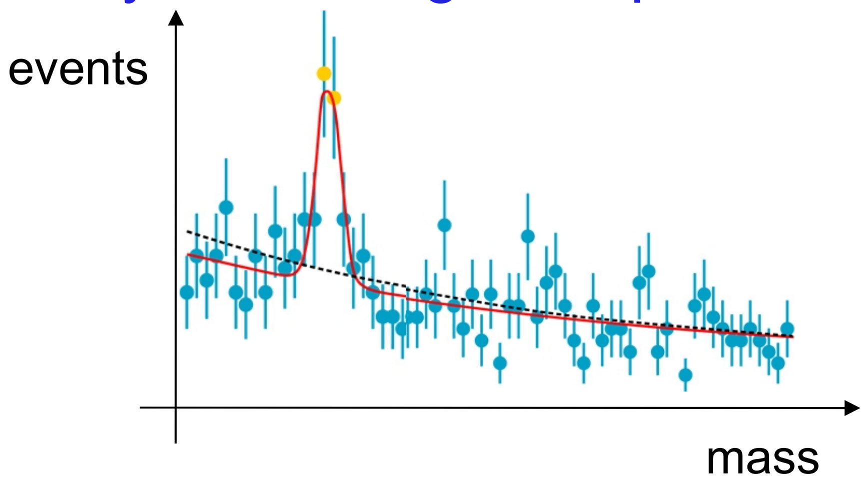
Onia in Heavy Ion Physics

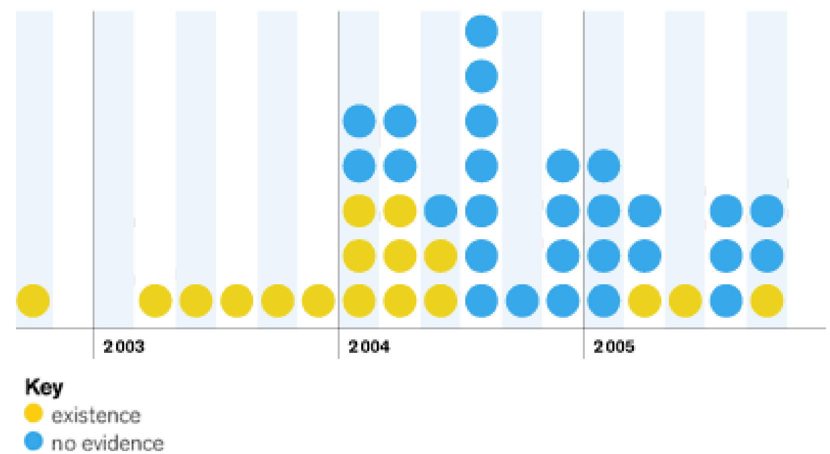
- naïve consideration of Debye screening analogy in quark gluon plasma
- onia form a simple color dipole
- high excited states disappear first
- finally onia disappear all together

Recent Excitement in Spectroscopy

In the last 4 years spectroscopy had a revival

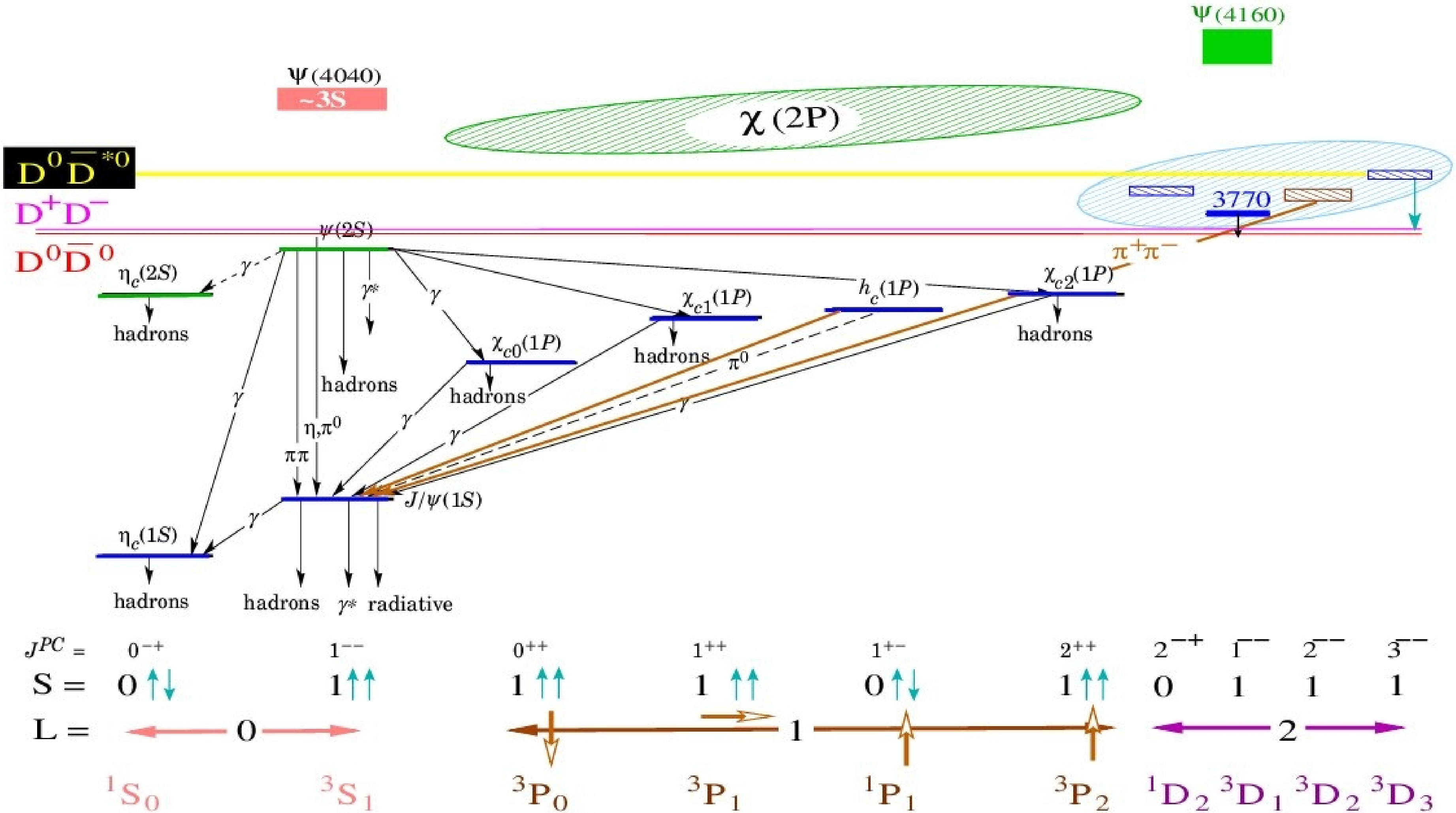
- penta quarks (observations 2003 turned out not to be real)
  - very interesting example how things can go wrong in spectroscopy





  - typical 'observation' plot .. and statistics of observation/null results
  - penta quarks: particles containing 5 quarks (meson 2, baryon 3 ...)
- new excited states of the D_s meson
- excited charmonia or new types of matter? Observations are real but what do they represent? ex. *X(3872)* follows

Overview of Charmonia



Usual complex picture of energy states

- ^xD_y candidates are next to be tackled
- mass predictions are at 50 MeV level, but not rock solid

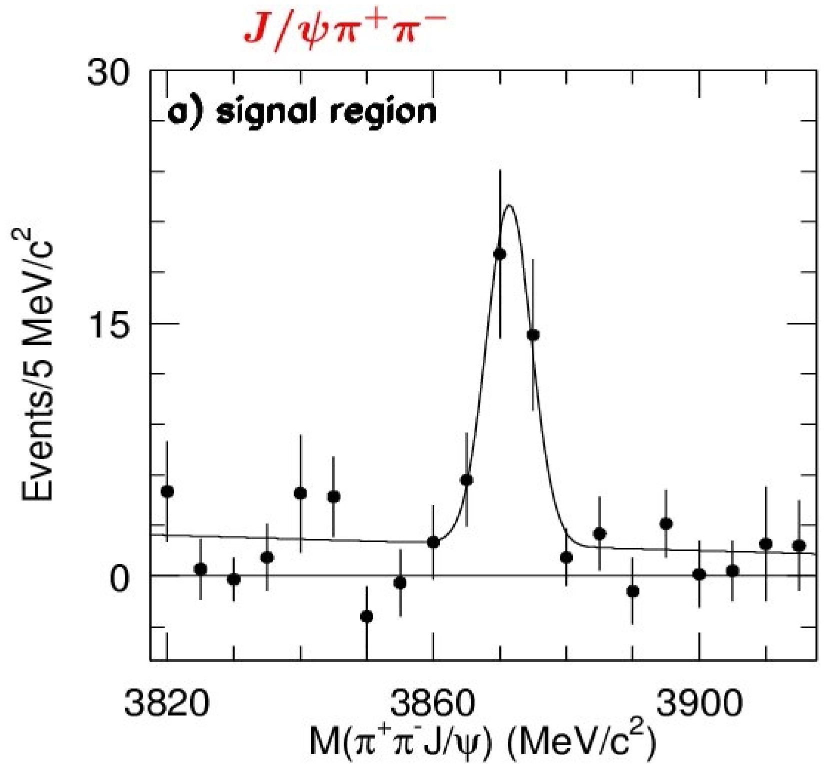
Observation of the X(3872)

In August 2003 Belle announced

- looking for the next charmonium state ($^3D_2$)
- new particle at energy ≈ 3872 MeV in decay to $J/\psi\ \pi^+\pi^-$
- confirmed very shortly afterwards at CDF

Search strategy at Belle (e^+e^-)

- in decay $B^+ \rightarrow J/\psi\ \pi^+\pi^-\ K^+$
- events: 35.7 ± 6.8 10.3 std. deviations
- mass: 3872.0 ± 0.6 ± 0.5 MeV
- width: smaller 2.3 MeV (90% CL)
- is this a charmonium?



Nature of the Particle: What is it?

Coined the *X* because of its unclear nature

- obvious candidate: excited charmonium but mass different
- mass very close to *DD** threshold

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Observation of a Narrow Charmoniumlike State in Exclusive $B^{\pm} \to K^{\pm}\pi^{+}\pi^{-}J/\psi$ Decays

S.-K. Choi,[5] S. L. Olsen,[6] K. Abe,[7] T. Abe,[7] I. Adachi,[7] Byoung Sup Ahn,[14] H. Aihara,[43] K. Akai,[7] M. Akatsu,[20] M. Akemoto,[7] Y. Asano,[48] T. Aso,[47] V. Aulchenko,[1] T. Aushev,[11] A. M. Bakich,[38] Y. Ban,[31] S. Banerjee,[39] A. Bondar,[1] A. Bozek,[25] M. Bračko,[18,12] J. Brodzicka,[25] T. E. Browder,[6] P. Chang,[24] Y. Chao,[24] K.-F. Chen,[24] B. G. Cheon,[37] R. Chistov,[11] Y. Choi,[37] Y. K. Choi,[37] M. Danilov,[11] L. Y. Dong,[9] A. Drutskoy,[11] S. Eidelman,[1] V. Eiges,[11] J. Flanagan,[7] C. Fukunaga,[45] K. Furukawa,[7] N. Gabyshev,[7] T. Gershon,[7] B. Golob,[17,12] H. Guler,[6] R. Guo,[22] C. Hagner,[50] F. Handa,[42] T. Hara,[29] N. C. Hastings,[7] H. Hayashii,[21] M. Hazumi,[7] L. Hinz,[16] Y. Hoshi,[41] W.-S. Hou,[24] Y. B. Hsiung,[24,*] H.-C. Huang,[24] T. Iijima,[20] K. Inami,[20] A. Ishikawa,[20] R. Itoh,[7] M. Iwasaki,[43] Y. Iwasaki,[7] J. H. Kang,[52] S. U. Kataoka,[21] ... T. Kawasaki, ... H. Kichimi, ... E. Kikutani, ... H. J. Kim, ... Hyunwoo Kim, ... S. K. Kim, ... K. Kinoshita, ... H. Koiso, ... P. Koppenburg, ... S. Korpar, ... P. Križan, ... P. Krokovny, ... S. Kumar ...

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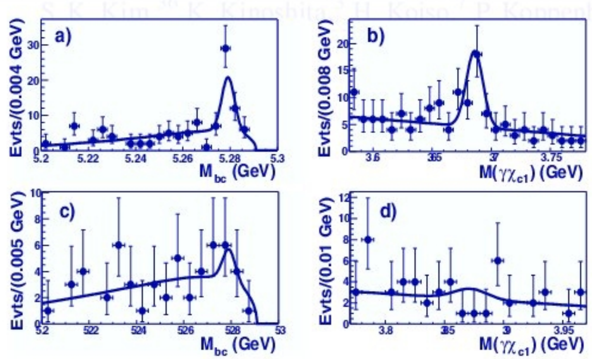

FIG. 4 (color online). Signal-band projections of (a) M_{bc} and (b) $M_{\gamma\chi_{c1}}$ for the ψ' region with the results of the unbinned fit superimposed. (c),(d) The corresponding results for the $M =$ 3872 MeV region.

This mass value and the absence of a strong signal in the $\gamma\chi_{c1}$ decay channel are in some disagreement with potential model expectations for the $^3D_{c2}$ charmonium state. The mass is within errors at the $D^0\bar{D}^{*0}$ mass threshold (3871.1 ± 1.0 MeV [9]), which is suggestive of a loosely bound $D\bar{D}^*$ multiquark "molecular state," as proposed by some authors [1,19].

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hypothesis of DD* molecule

Big deal: new type of binding – QDC

CDF Charmonia

Look at charmonia at the TeVatron

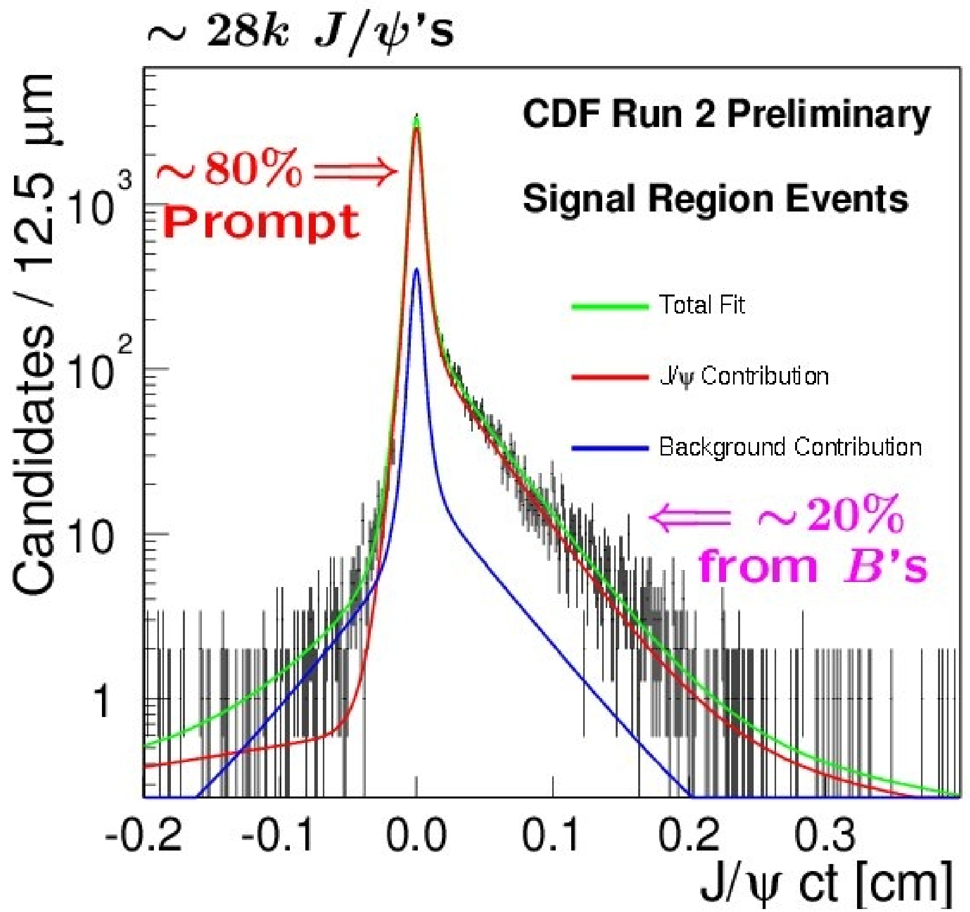
- classic example is $J/\psi \to \mu\mu$: prompt versus $B \to J/\psi X$
- B longer lived so J/ψ is displaced: ≈20% from B

Muon decay is crucial

- muons are clean (lecture 11)
- trigger is simple and low rate

Separate prompts

- use silicon detector
- achieve statistical separation

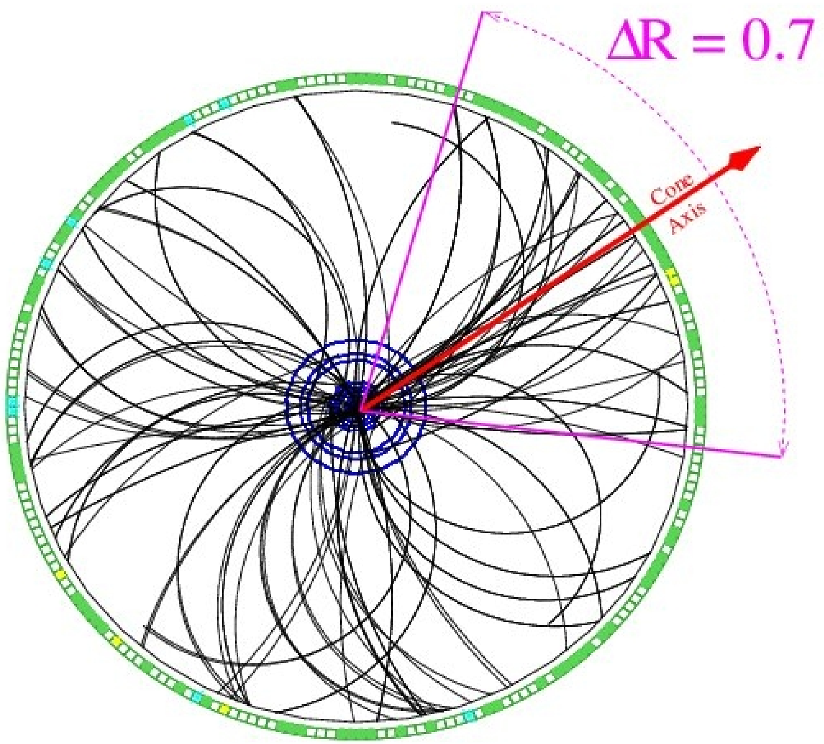


One of standard candles for calibrations

CDF Observation of X(3872)

Combinatorics the killer

- most X(3872) expected prompt
- clean $J/\psi \rightarrow \mu\mu$ but two more pions: $X \rightarrow J/\psi\pi^+\pi^-$ many possibilities
- restrict phase space: p_T, angles
- calibrate with: $\psi' \rightarrow J/\psi\pi^+\pi^-$
- almost same kinematics



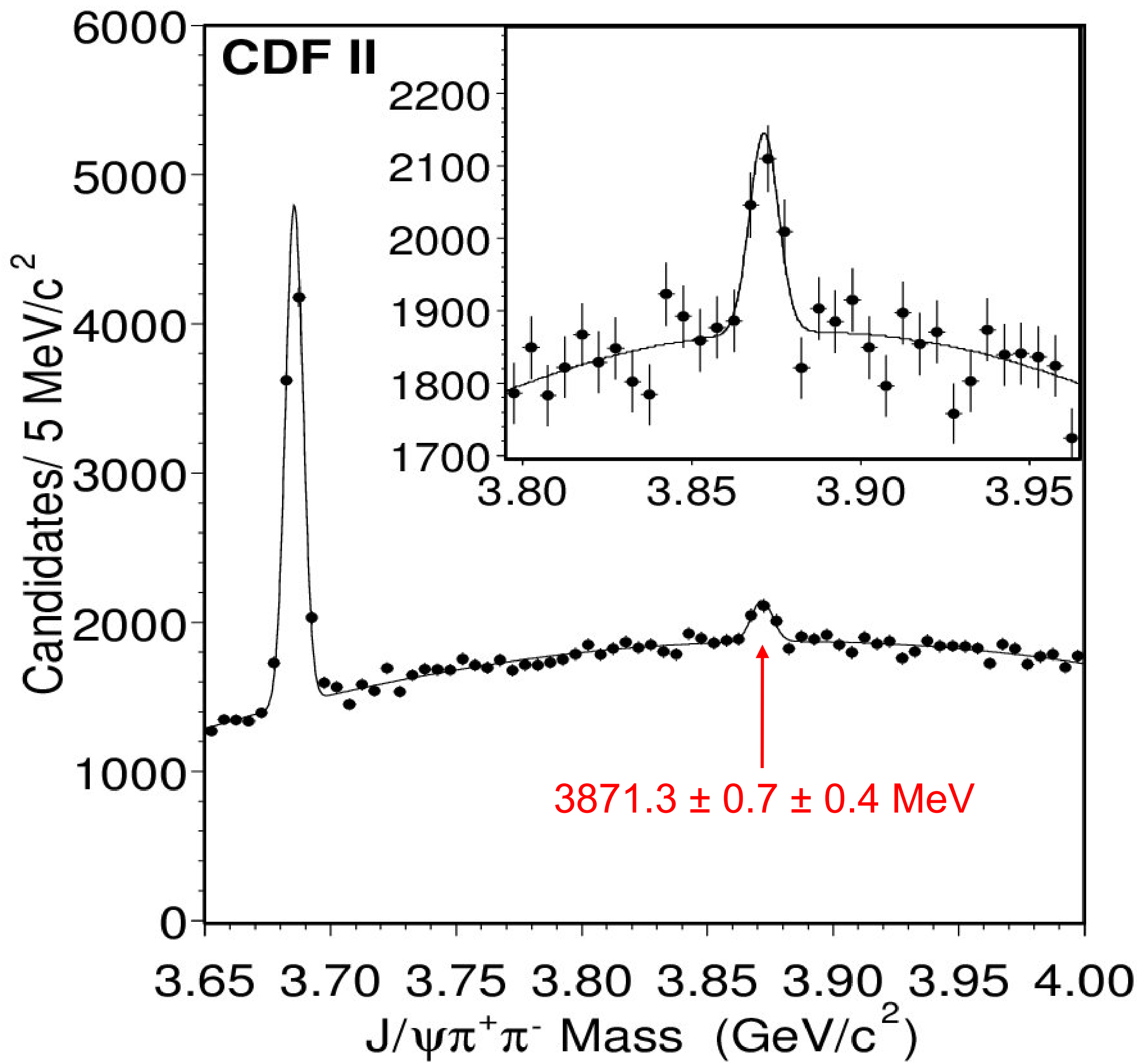
Analysis optimization

- based on $\psi' \rightarrow J/\psi\pi^+\pi^-$
- optimize statistical significance

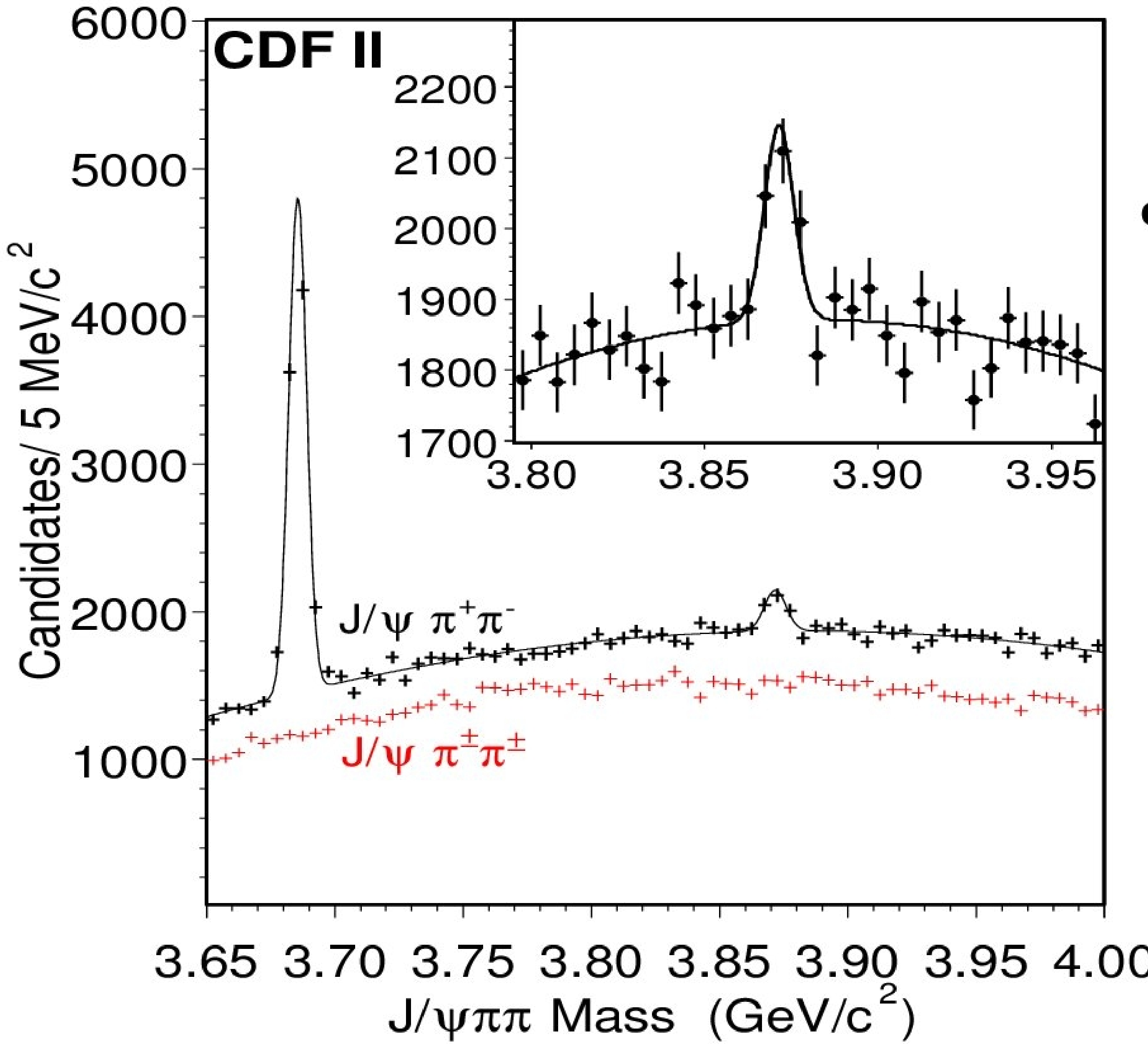
CDF Observation of X(3872)

Properties

- lumi 220 pb^{-1}
- large ψ' peak
- about 600 candidates



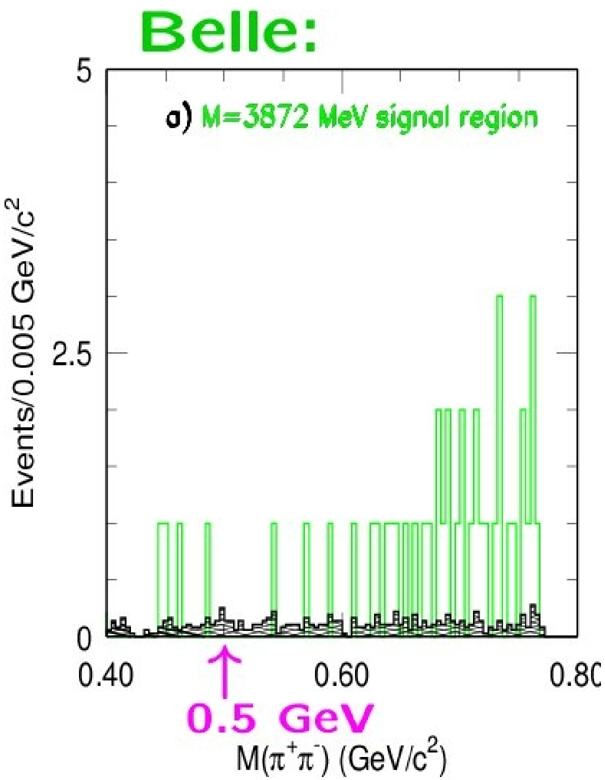
CDF Observation of X(3872)



Wrong sign *ππ*

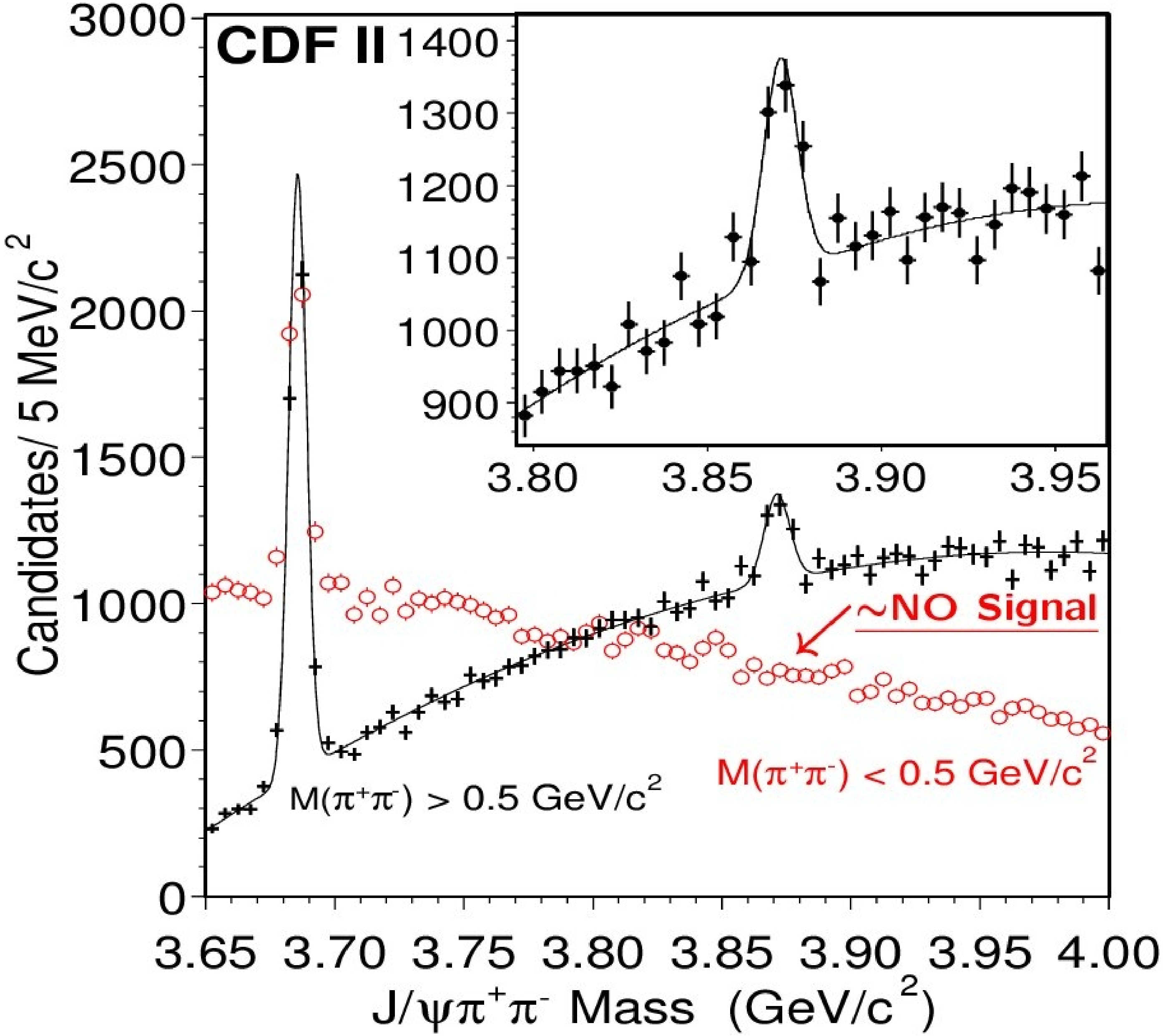
- no signal

CDF Observation of X(3872)



From Belle

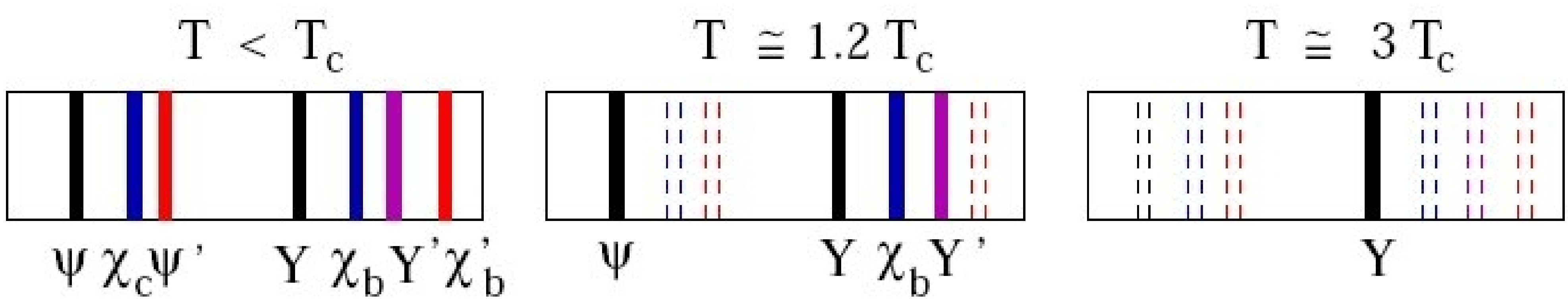
- $m(\pi\pi)$ large
- require:
  - $m(\pi\pi)$>500 MeV



Screening in Heavy Ion Collisions

Quark Gluon Plasma

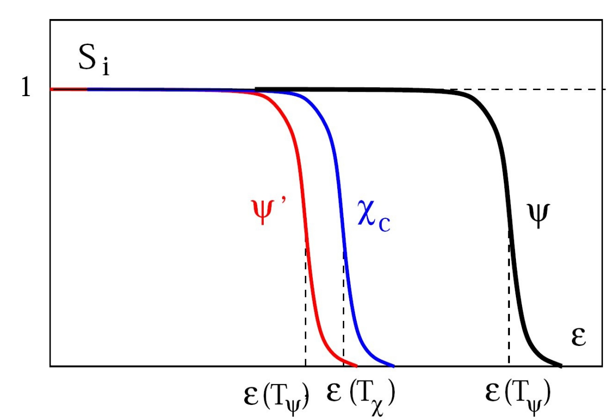
- de-confined color charges
- color charge screening for color dipoles: $q\bar{q}$
- screening radius decreases with temperature: $\lambda_D(T)$
- at critical temperature T_C onia radii equal Debye length
- states begin to disappear, starting from the 'largest' ones



Disappearance of Onia

Experimental signature

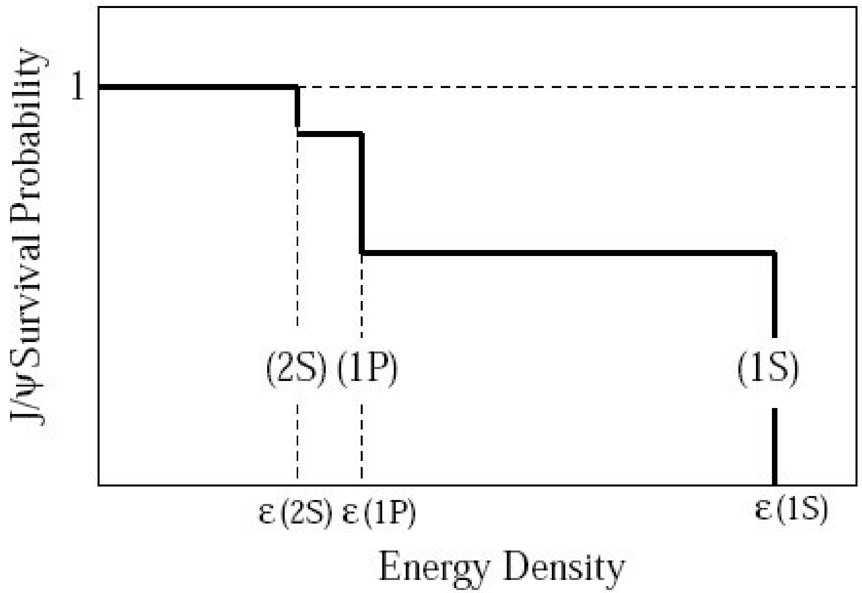
- vary temperature of quark gluon plasma
- carefully observe the various onia and their excited states
- determine dissociation point as T_i as $\lambda_D(T_i) = r_i$
- gradual disappearance should manifest as changes in the measured cross sections
- avoid overall normalization by measuring ratios with respect to the lowest (and most stable) state
- variation of the temperature achieved by variation of collision energy and centrality of the collision

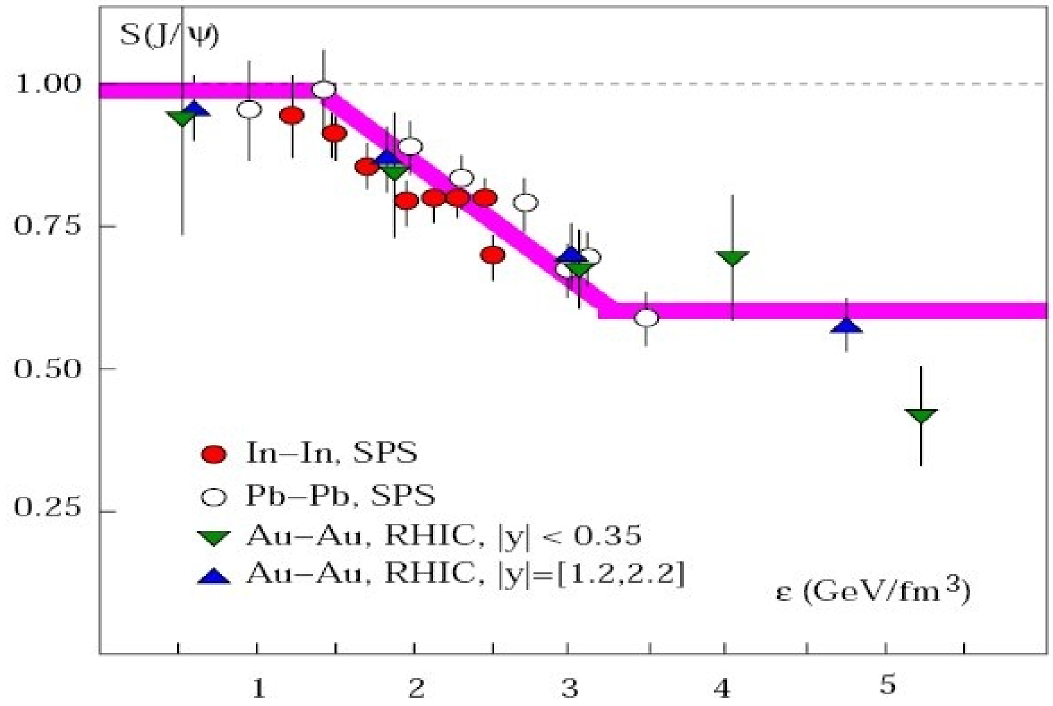


Caveats

SPS/RHIC experiments

- *J/ψ* suppression is observed, but due to *J/ψ* dissolving?
- due to dissolving higher states which decay to *J/ψ*, sequential suppression?
- re-combination possible: many *c* quarks produced in hard process
- effect cancel: p_T spectrum





Conclusion

Quarkonia revolutionized HEP

- charmonium: *J/ψ* (November revolution, 1974)
- bottomonium: third and so far last family of fermions
- spectroscopy interesting as non perturbative QCD playground

Quarkonia a key signature in Heavy Ion physics

- disappearance of *J/ψ* in SPS data interpreted as QGP
- there are doubts though: opposite sign effects
- bottomonia should behave much better and are one key probe for the LHC
- we are going to look at *Upsilon* production rates in CDF data as normalization

Next Lecture

Detectors: Electron/Muon Detection and Particle Id

- electromagnetic calorimetry
- muon chambers
- particle identification systems
  - dE/dx in drift chamber
  - TOF – Time-Of-Flight detectors
  - RICH – Ring Immaging CHerenkov detectors
  - DIRC – Detection of Internall Reflected Cherenkov light