Tevatron Results

Tom Junk

Fermilab

LHC PhenoNet Winter School 2012
22-29 January
Ascona, Switzerland

Topics Discussed in the Three Lectures

1) QCD and B-Physics
2) Electroweak, Top, and Exotics
3) Higgs Boson Searches

Tevatron Results 1: QCD and B Physics

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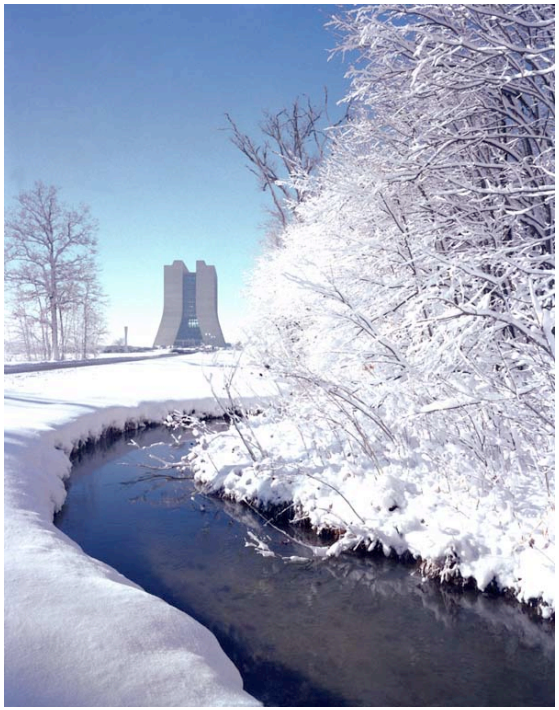
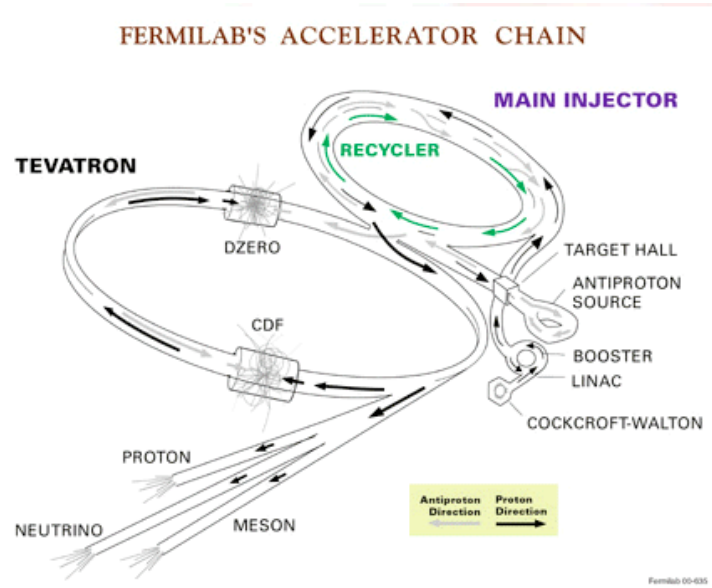
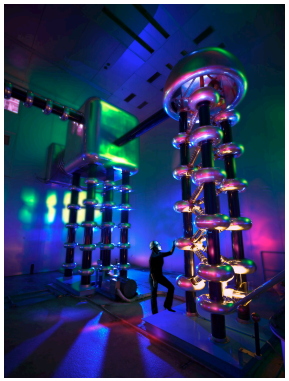


- Introduction to the Tevatron
- CDF, D0, and their respective capabilities
- Inclusive and Exclusive Production of photons
- W Forward-Backward Asymmetry
- $B_s \rightarrow \mu\mu$
- Charmless B decays
- B_s mixing and CP violation
- Upsilon Polarization
- B Baryons

The Tevatron and Associated Accelerators





Cockroft-Walton

Linac

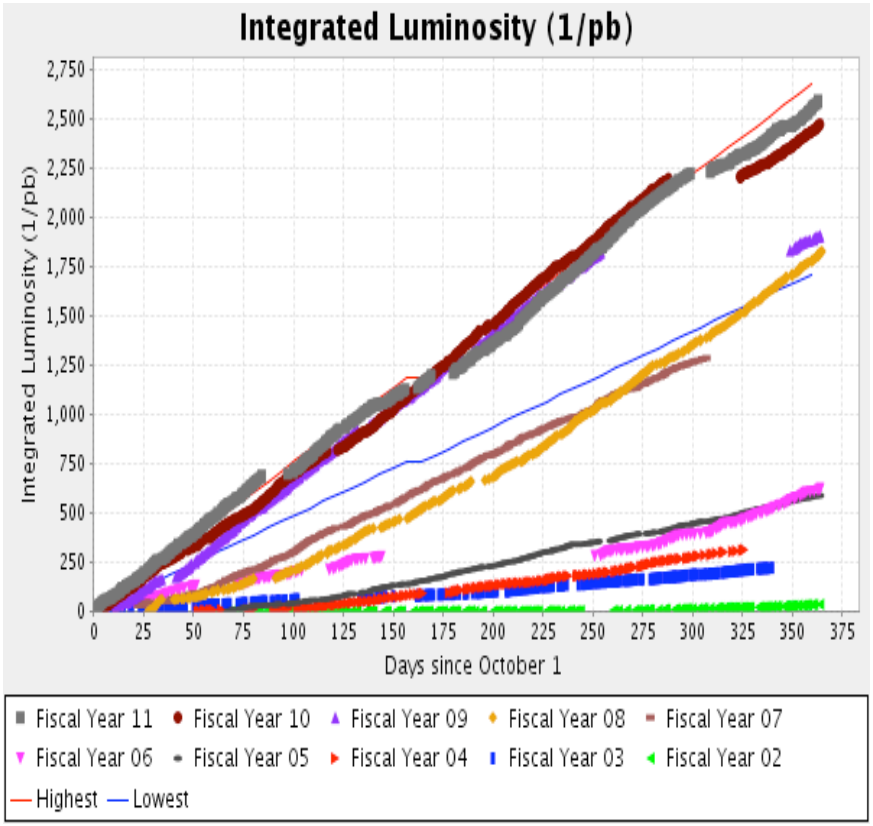
Booster

pbar debuncher and accumulator

ppbar collisions at 1.96 TeV
Luminosity up to 400E30 $cm^{-2}s^{-1}$
A very good week: ~80 pb^{-1}

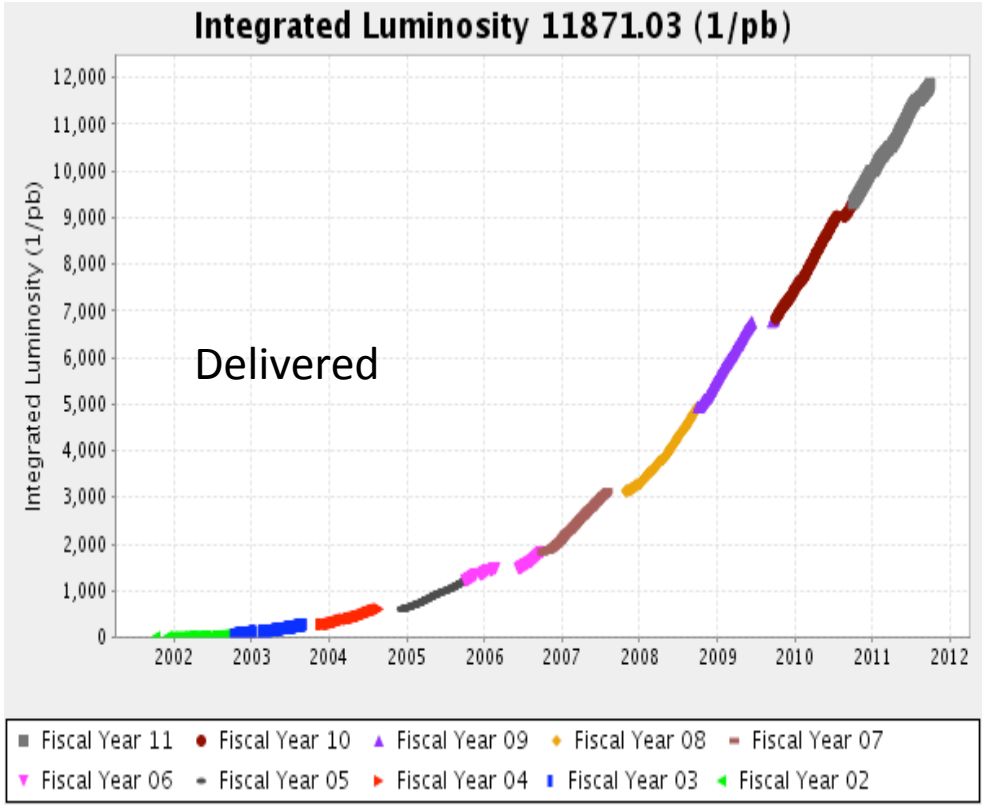
Tevatron Performance Improved over the Years

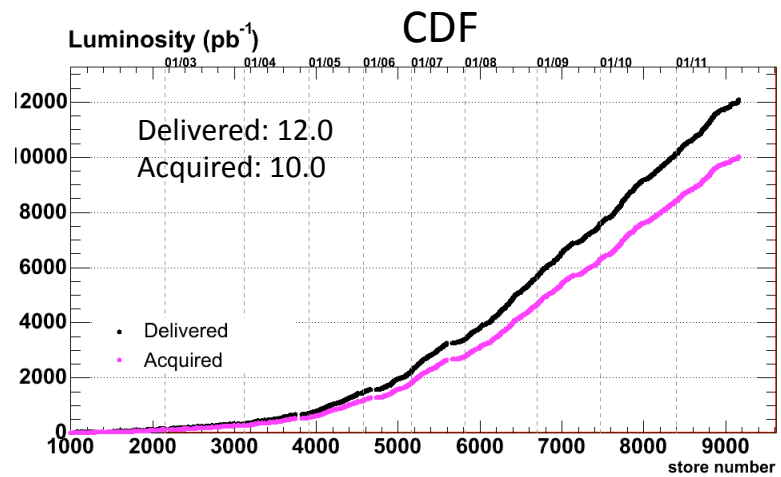
A partial list of improvements:

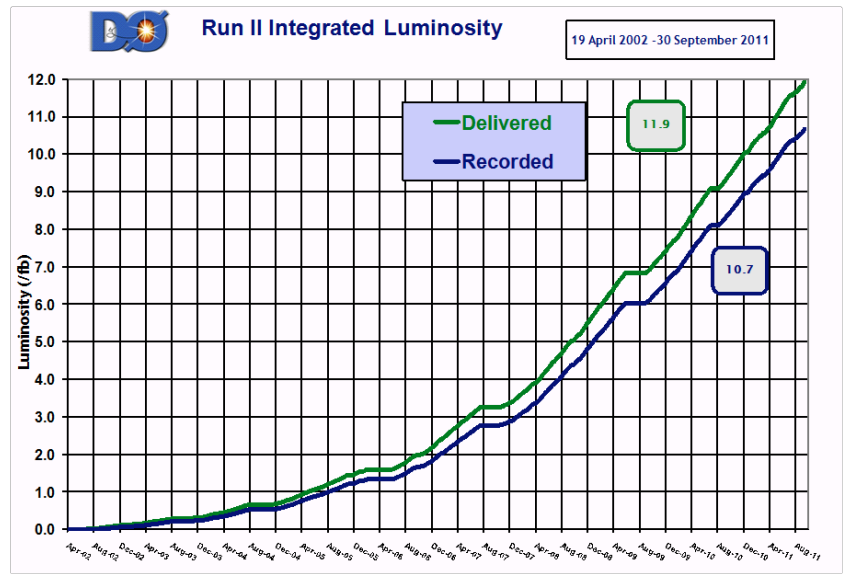


- Store antiprotons in recycler
- Faster transfers from pbar accumulator to recycler
- Electron cooling of pbars in recycler
- Efficiency and reliability of injection
- Faster shot setup
- Separation of orbits at parasitic crossings
- Replacement of 1200 He relief valves
- Faster beam aborts during quenches
- "cogging" pbars to prevent quenches during acceleration

Integrated Luminosity Delivered and Acquired

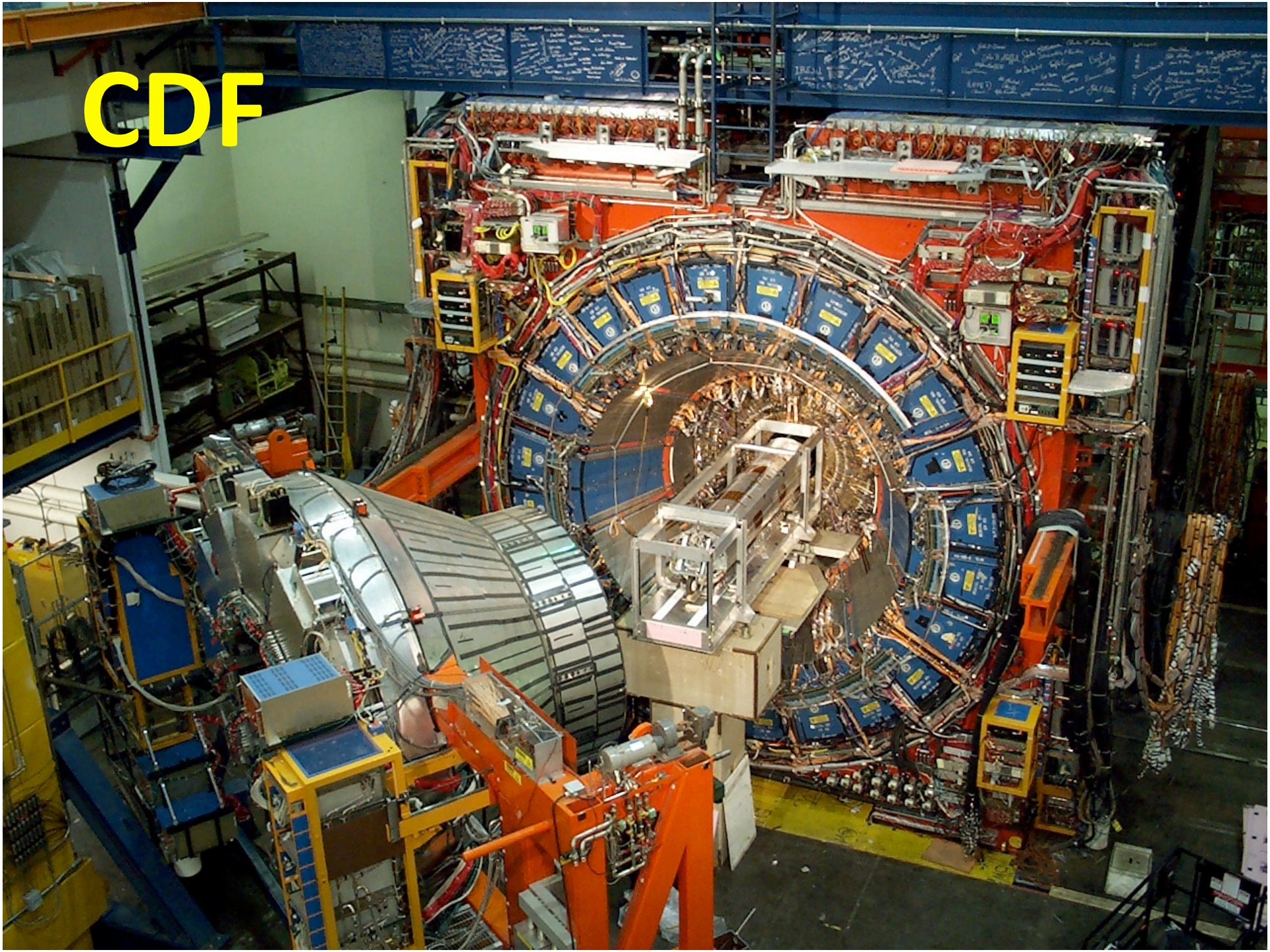




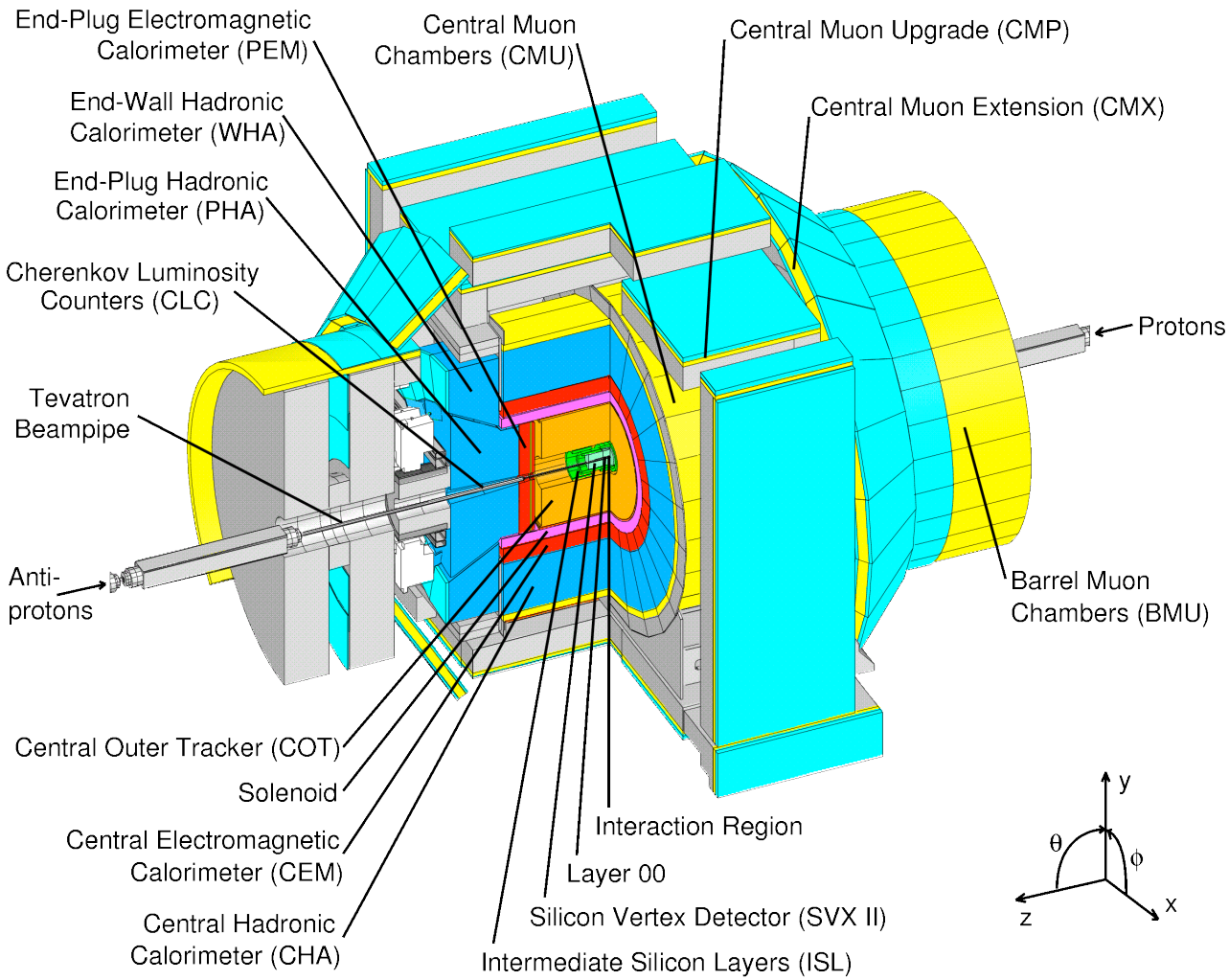


Reasons for lower acquired data:

- trigger and readout deadtime
- HV ramp-up at beginning of store and trips
- DAQ resets and other problems
  (radiation causes glitches in sensitive electronics in the collision hall)


CDF

The CDF II Detector



Lepton coverage:
$|\eta| < 1.5$ (muons)
$|\eta| < 2.0$ (electrons)

b-tagging with
$|\eta| < \sim 1.4$

Jets to
$|\eta| < 2.8$
Higgs analyses restrict to
$|\eta| < 2.0$

Dijet mass resolution: ~16%

CDF Run II Trigger System

Bunch Crossing Rate: ~1.7 MHz

Level 1 trigger ~15 KHz

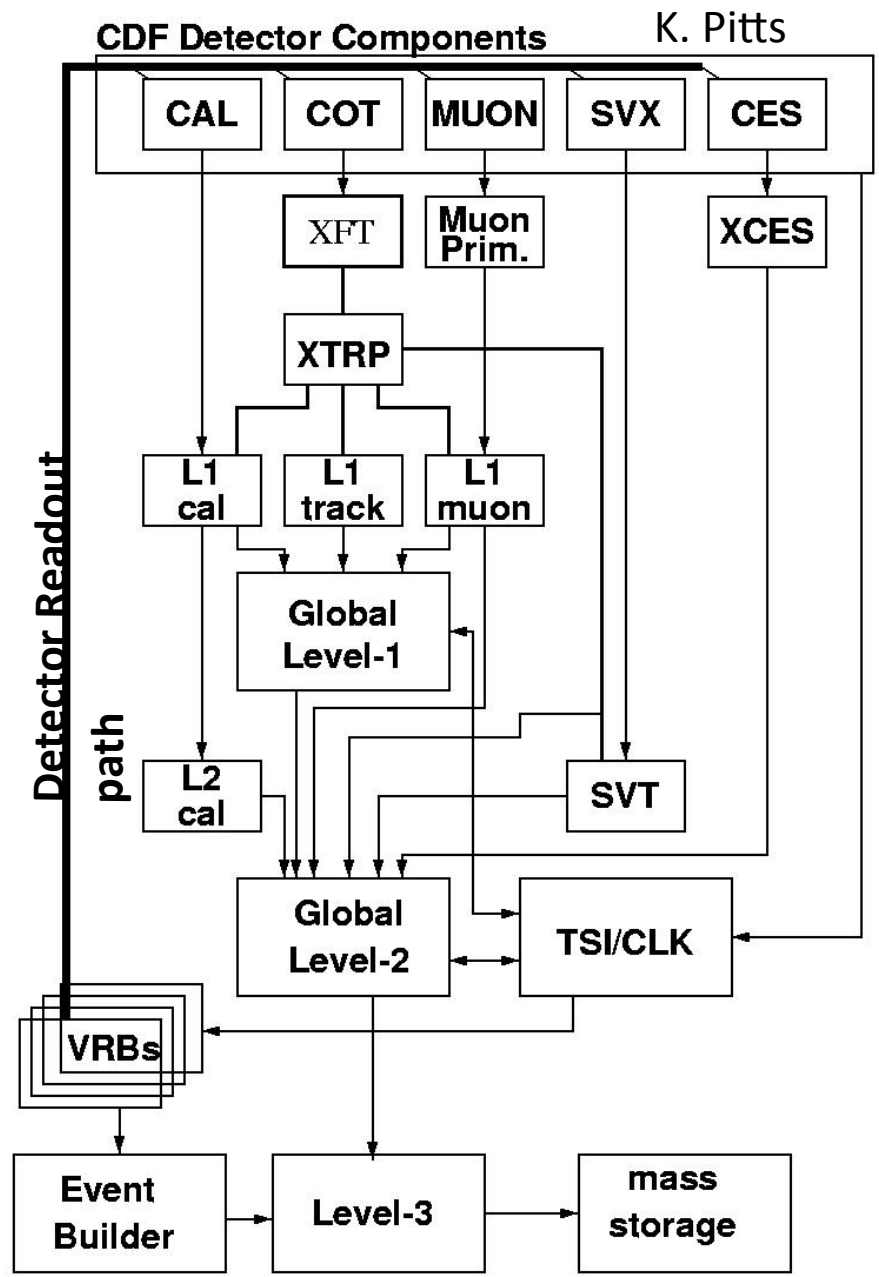
- tracking
- calorimeter: jets & electrons
- muons

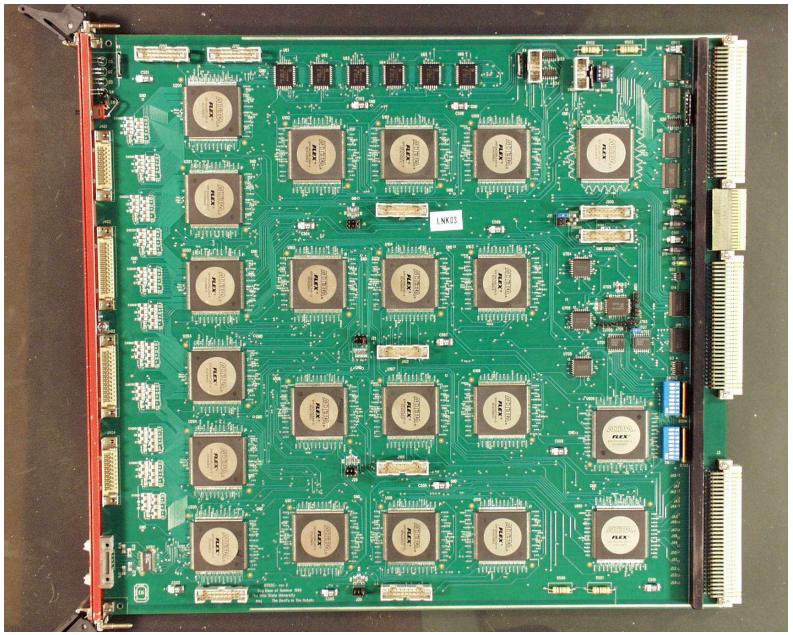
Level 2 trigger ~800 Hz

- L1 information (tracks, e, μ)
- calorimeter shower max
- silicon information
- algorithms run in L2 processor

Level 3 trigger ~200 Hz to tape

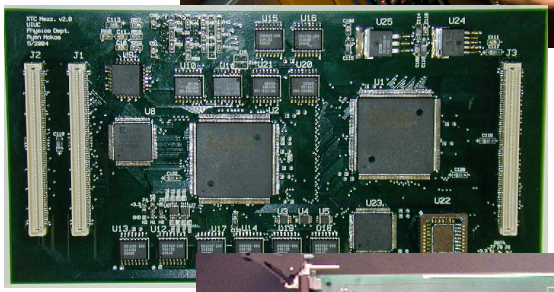
- full detector readout
- event building
- "offline" processing



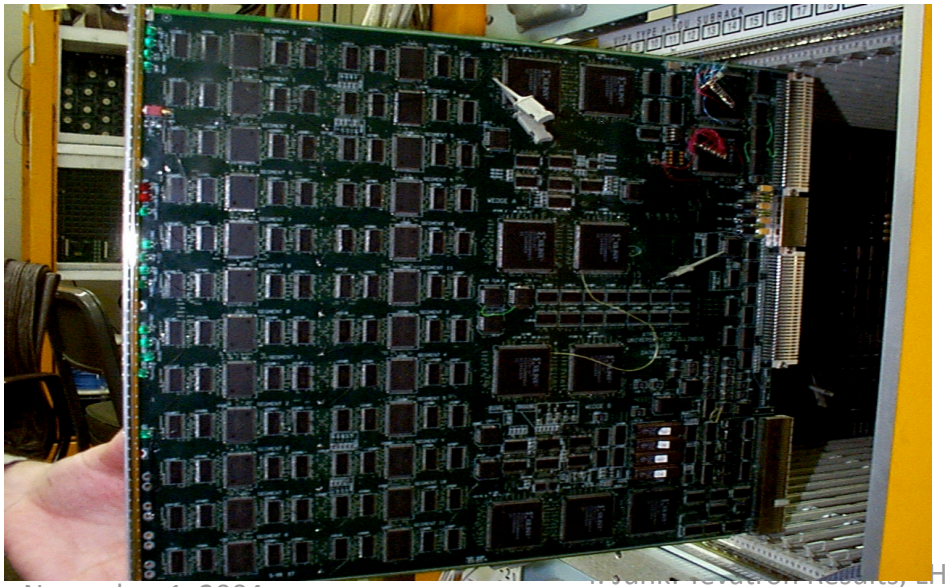


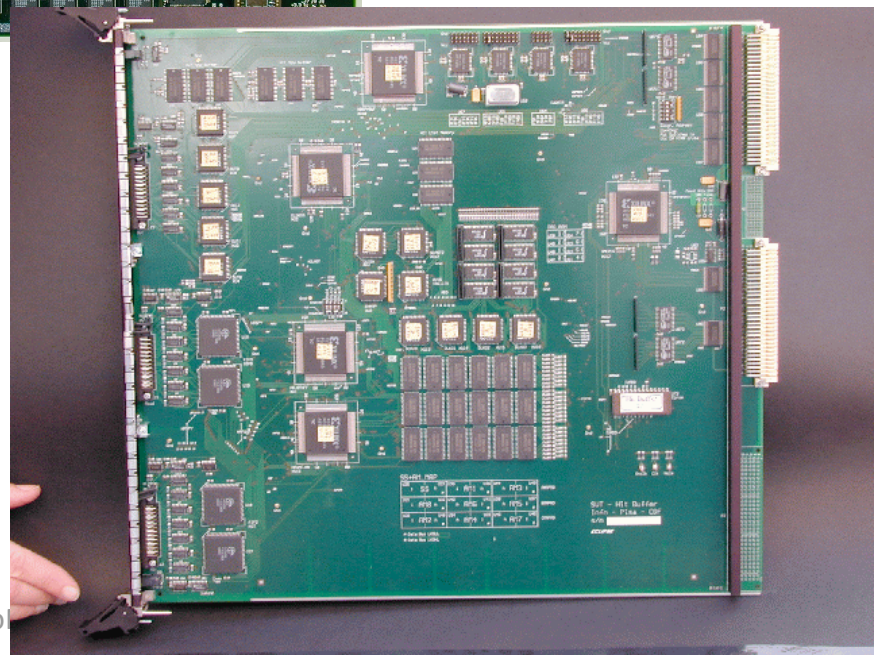
K.Pitts

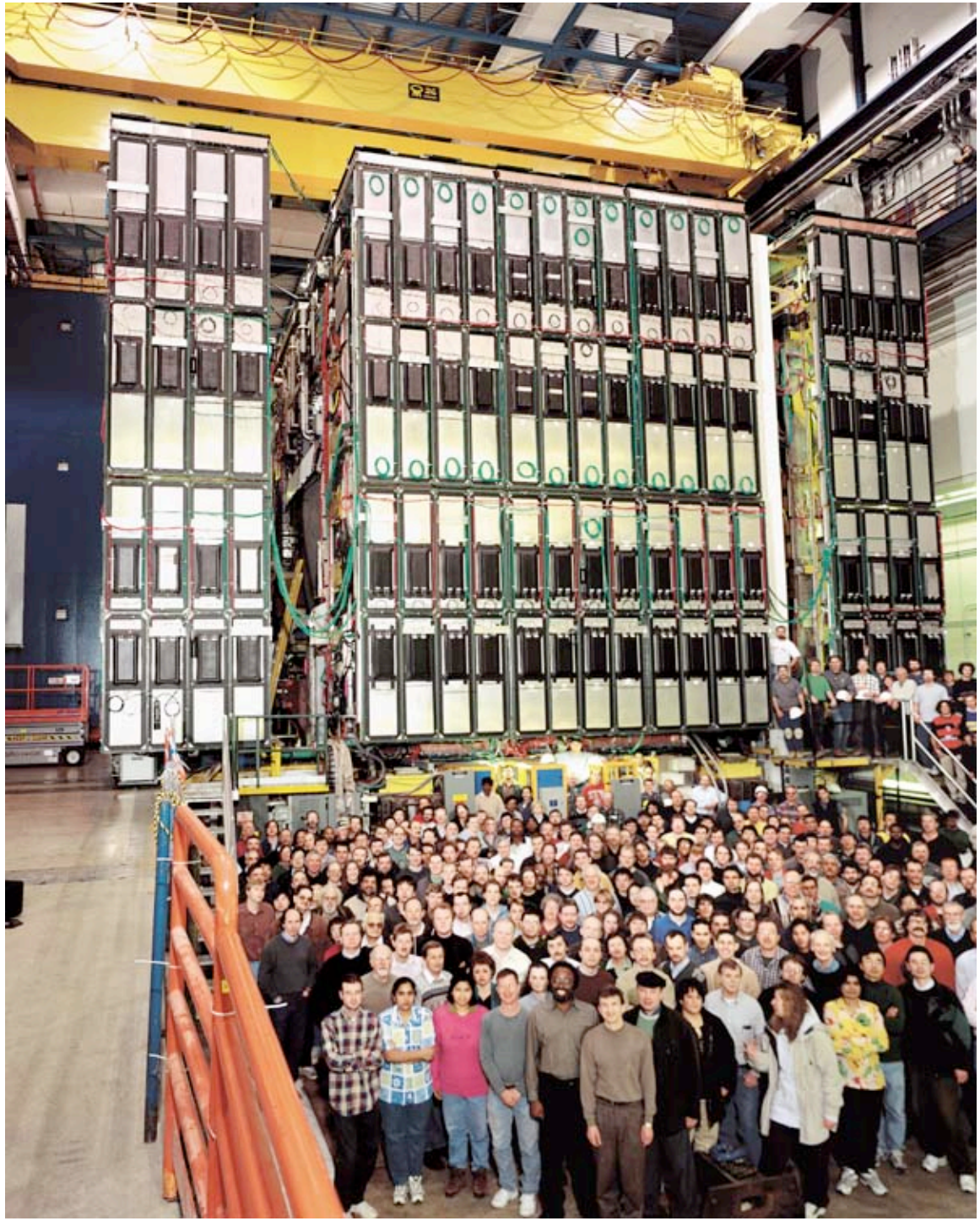
Hundreds of application- specific boards working together, passing and processing data on the nanosecond timescale…



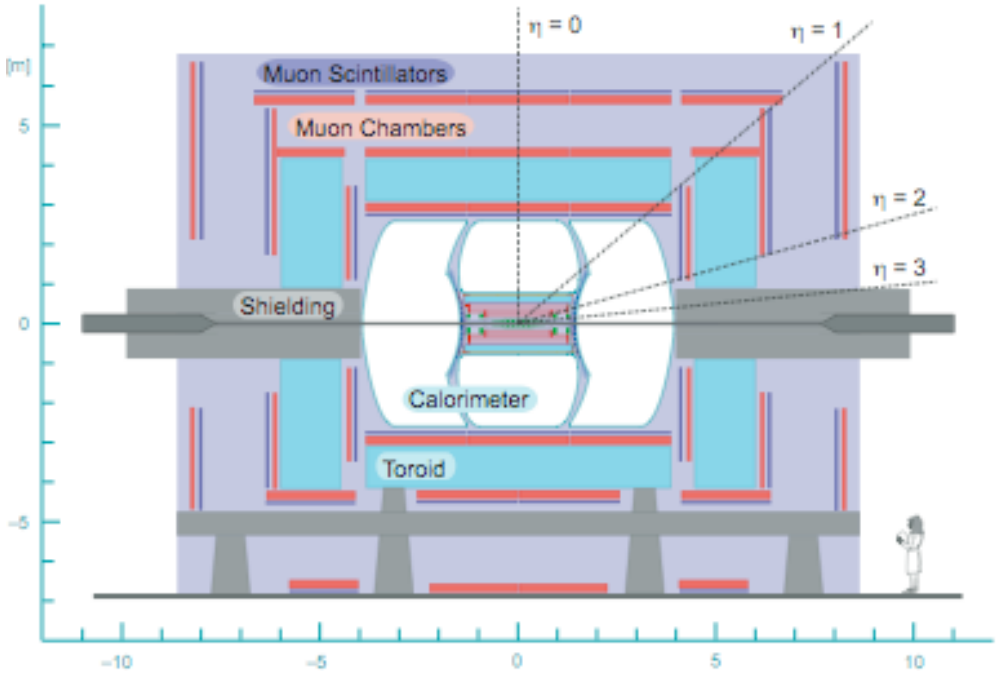
System continually upgraded to deal with increasing luminoity/ pileup

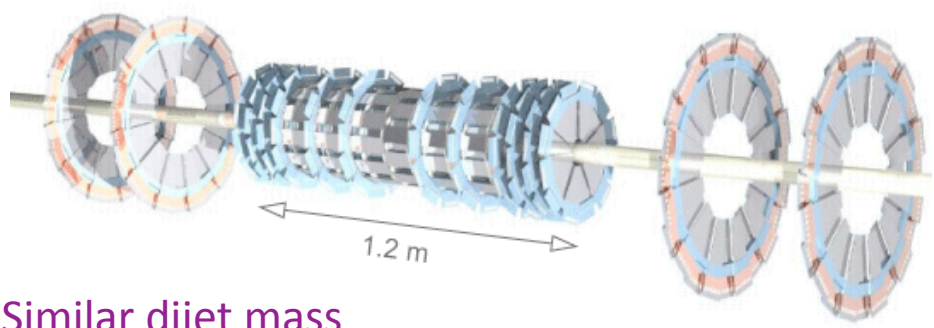






The DØ Detector





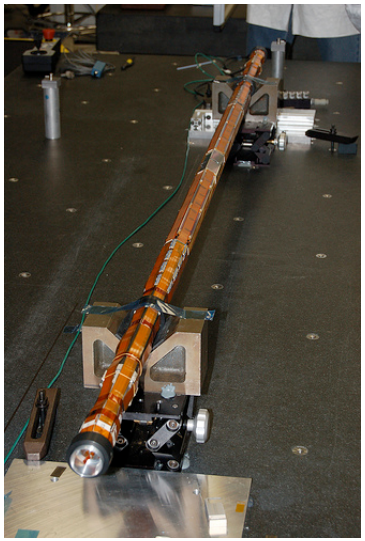
Lepton coverage:
|η| < 2 (muons)
|η| < 2.6 (electrons)

b-tagging with
|η| < ~2

Jets to
|η| < 3

Scintillating fiber tracker

Trigger similar to CDF's



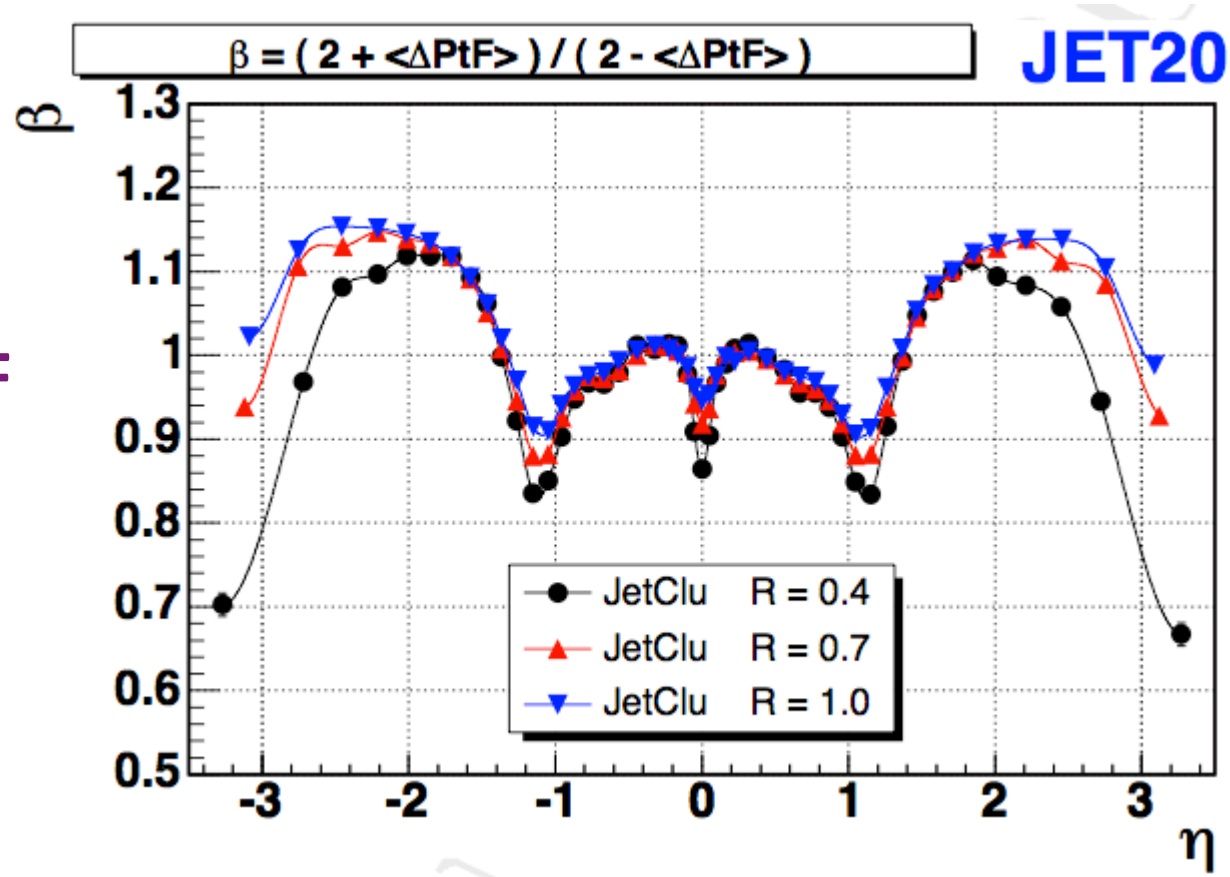
Similar dijet mass resolution to CDF

Good Feature: Regular Switching of Solenoid Field – Cancels Some Systematic Uncertainties

New Innermost Silicon Layer added between Run IIa and Run IIb

Uncorrected Jet Response is Highly angle dependent

CDF

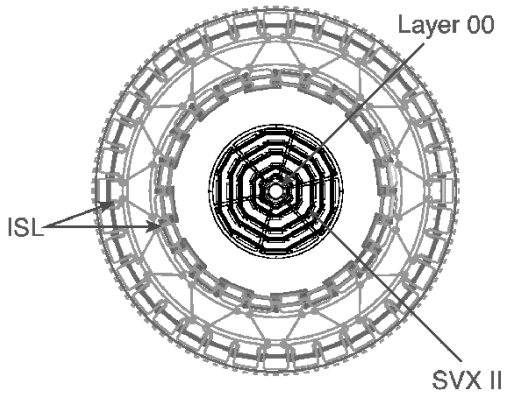


This is corrected out, but then the jet resolution is highly angle dependent.

Aside: Building a jet clustering algorithm into the trigger is a great way to ensure it never gets changed. Untriggered data are lost forever!

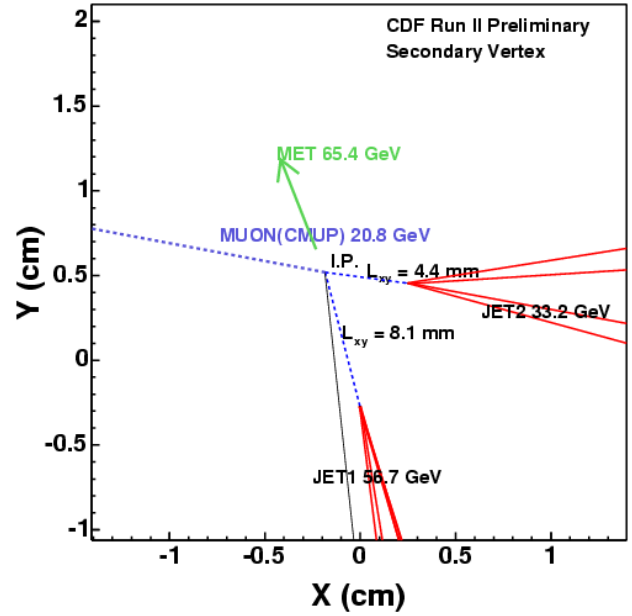
B-Tagging

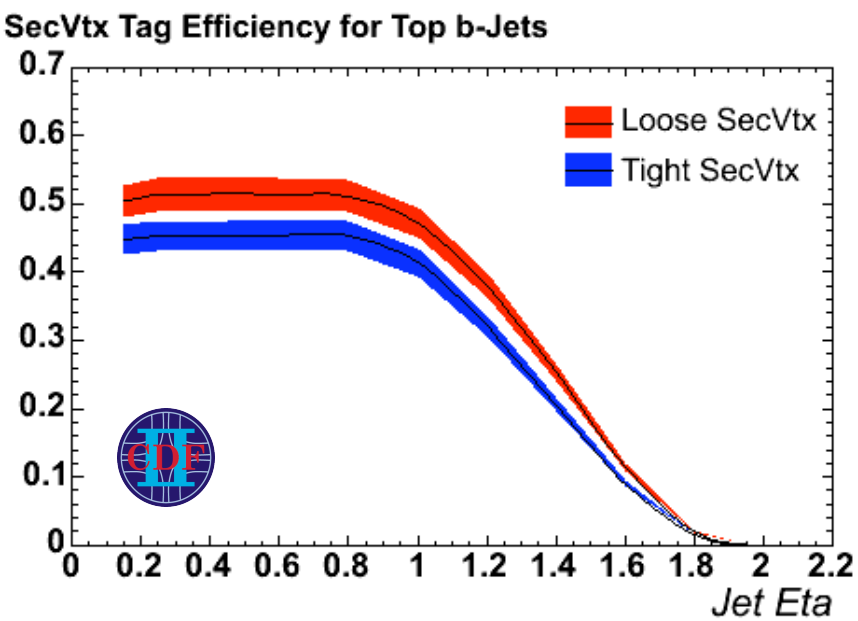
L00 single-sided silicon +
5-layer double-sided silicon+
2-layer ISL



Impact parameter resolution for high-p_T tracks ~18μm

B-tagging relies on displaced vertex reconstruction:
high mass, long lifetime





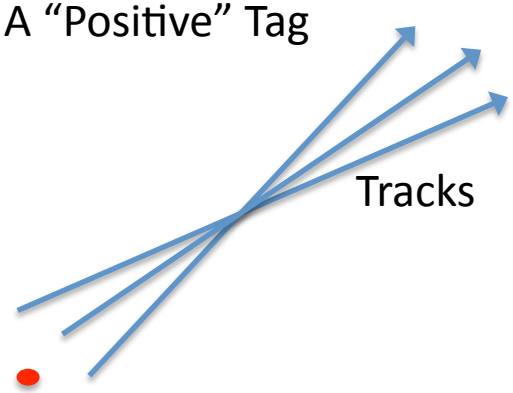
Mistag rates typically ~1% for light-flavor jets

Example candidate event (lvbb)

D0 B-tagging per-jet efficiency = 50-70% (of taggable jets) for 1-5% Mistag rate

B-Tagging Calibration

A "Positive" Tag

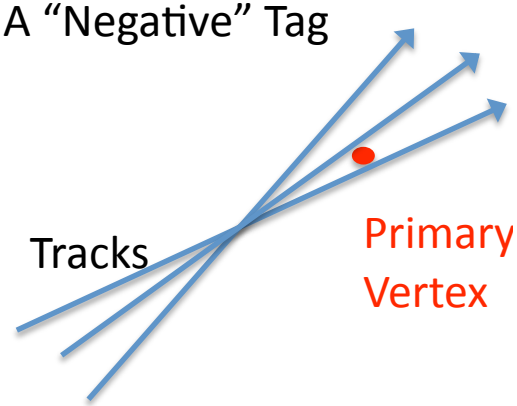


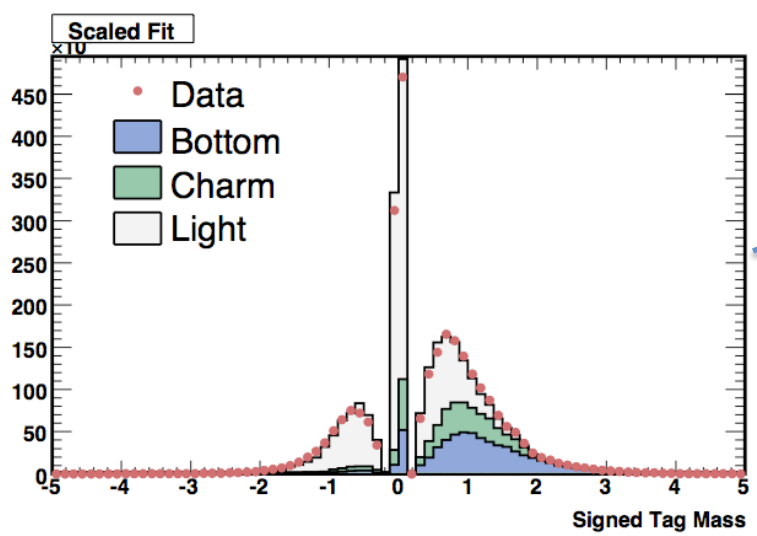
Fake tags calibrated with data – resolution dominated negative tags.

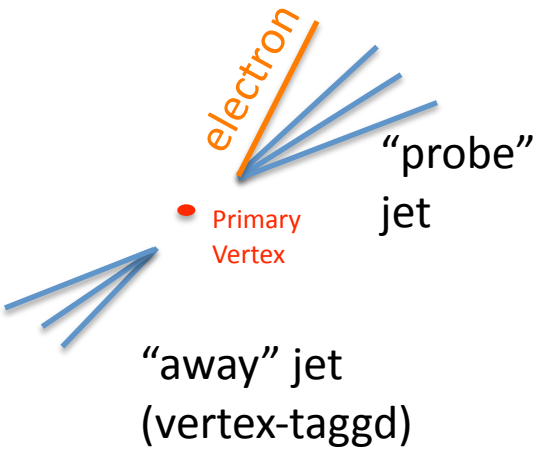
Watch out for asymmetry: scatters in detector material and long-lived strange particles cause more positive mistags than negative ones

Positive b-tags Calibrated in data with a sample of dijets – "away" jet is b-tagged, "probe" jet has a high-$P_{T,rel}$ electron. Tag rates compared in data and MC

A "Negative" Tag



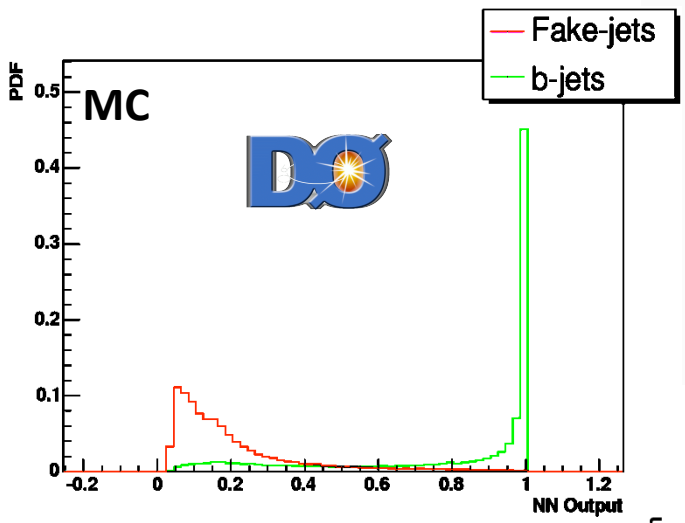


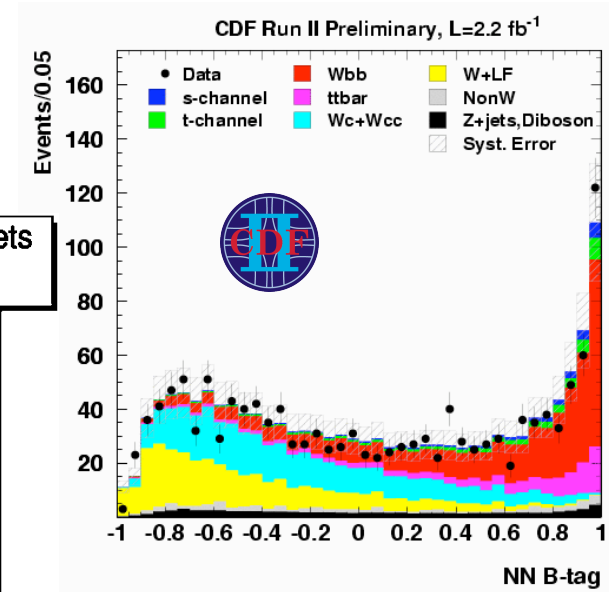


Neural Networks for Better B-tagging

CDF: Train a NN to separate b's from charm and light flavor jets in vertex-tagged jets

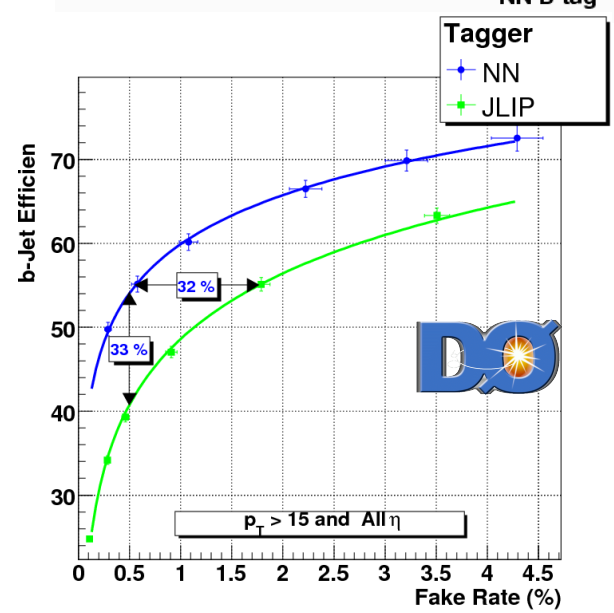
DØ: Use the NN as the b-tagging tool from the start. Choice of operating points.





Some of the inputs:

- Displaced vertex mass
- # tracks in displaced vertex
- Decay flight distance and significance
- Identified leptons in and near jets
- Secondary vertex fit χ^2
- Jet E_T

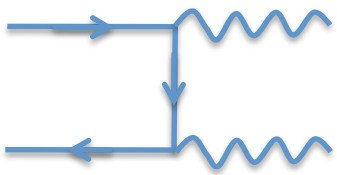


CDF and DØ: Efficiency and Mistags and NN's Calibrated with Data

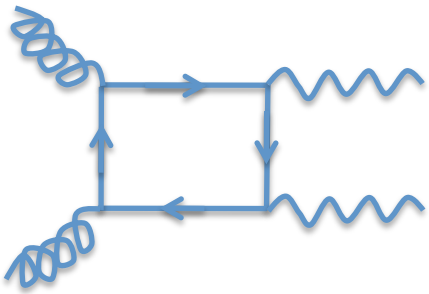
Inclusive Diphoton Production

- Background to H→$\gamma\gamma$ Search, heavy resonance search, and extra dimension search
- Test of pQCD and Monte Carlo implementations

Dominant production mechanism
qqbar → $\gamma\gamma$

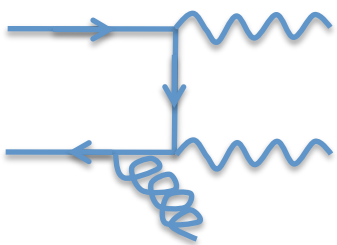


gg→$\gamma\gamma$ is less important
but contributes at low $m_{\gamma\gamma}$

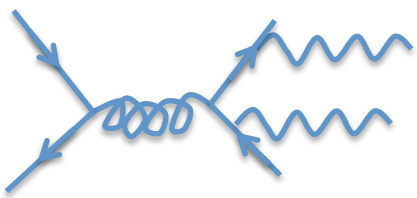


See L. Cieri's talk earlier today.

Diphoton Plus Jet(s)



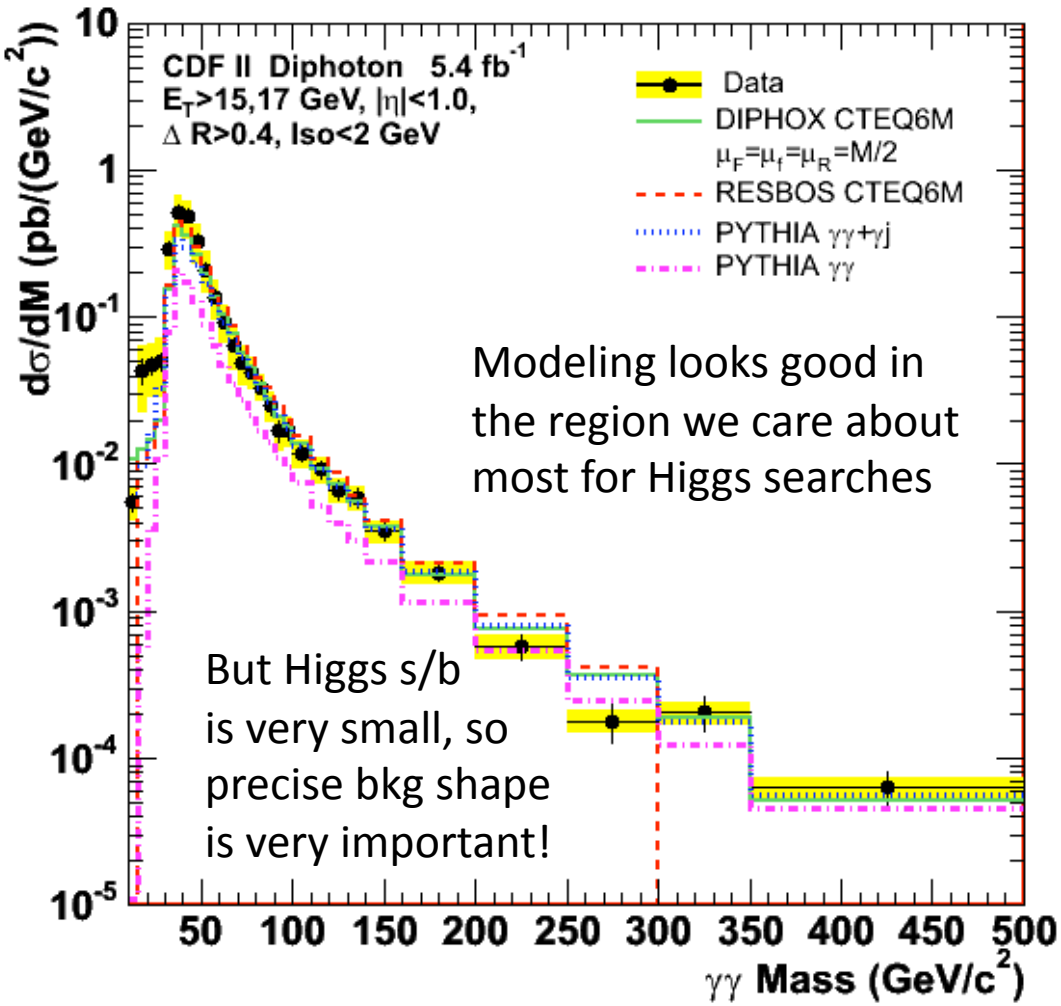
Jet(s) Plus Diphoton



At CDF, photons are selected with E_T>17 GeV (γ_1) and 15 GeV (γ_2), and |y|<1 for both photons (central calorimeter – also tracking coverage to reject electrons)
Isolation required – less than 2 GeV in a ΔR<0.4 cone around the photon (rejects multijet bkg).
Photons can "spoil each other's isolation"
Isolation requirement and nontrivial detector effects require the use of a full MC description including associated hadron production, UE, and pileup.

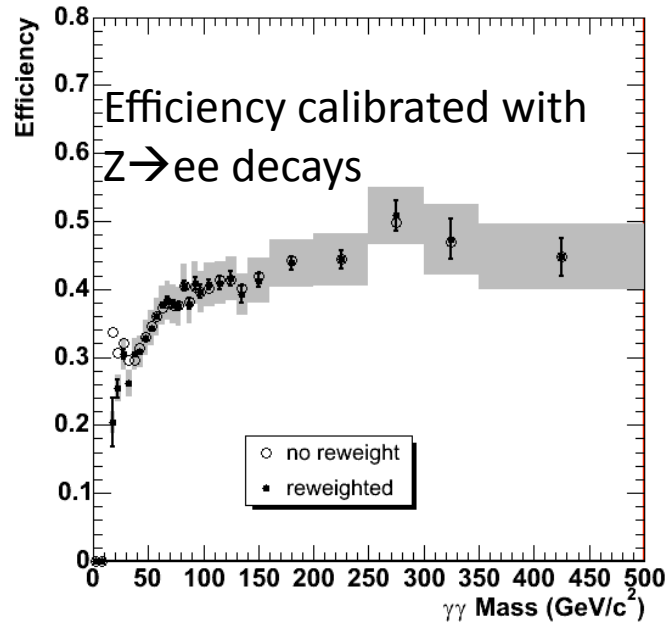
Inclusive Diphoton Production

CDF Collaboration, Phys. Rev. Lett. **107**, 102003 (2011)
Phys. Rev. D **84**, 052006 (2011)

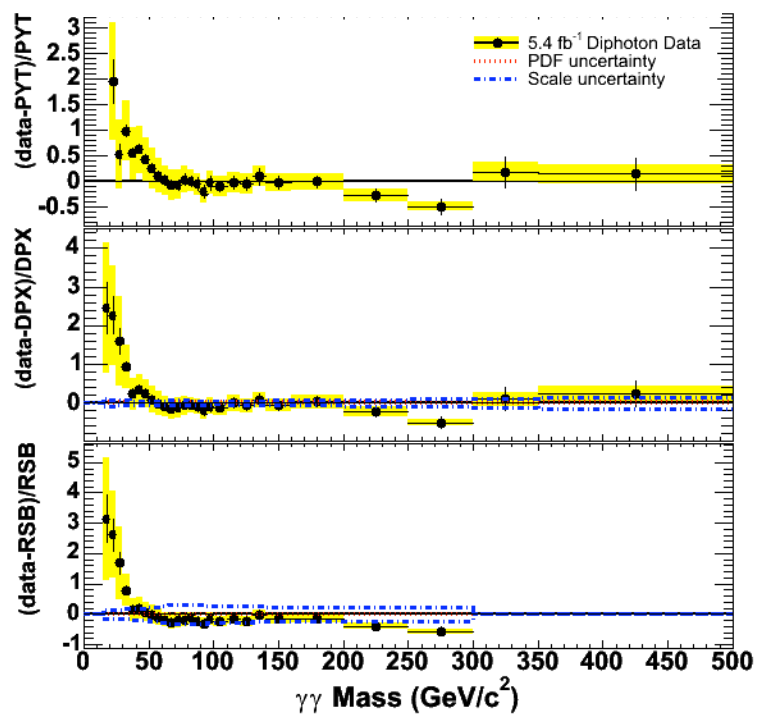


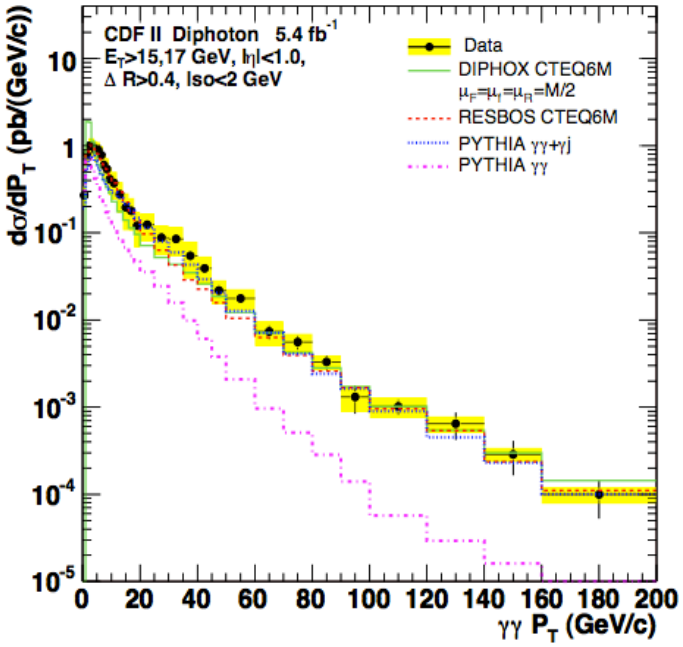
Modeling looks good in the region we care about most for Higgs searches

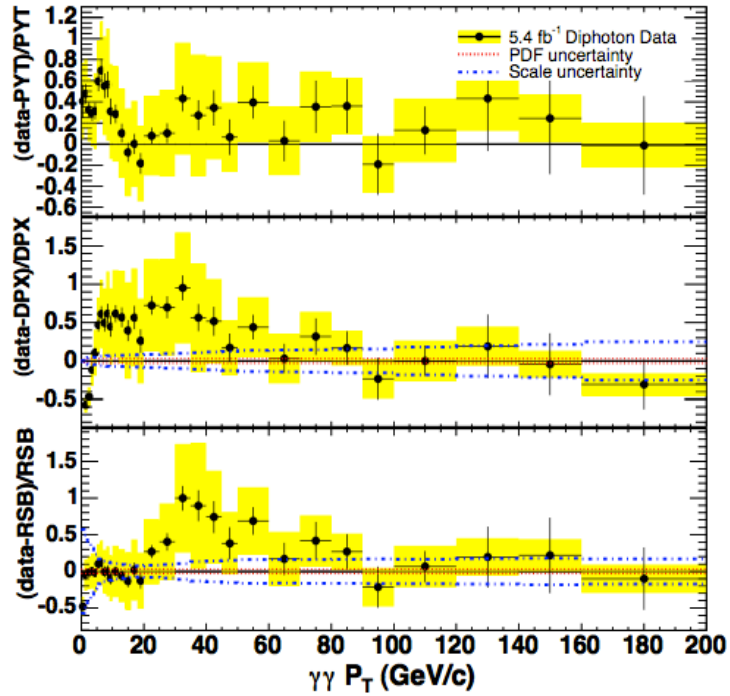
But Higgs s/b is very small, so precise bkg shape is very important!



Efficiency calibrated with Z→ee decays







RESBOS:
NLO Cross Section,
Resummed ISR
soft gluons

PYTHIA:
Parton shower

$$q\bar{q} \rightarrow \gamma\gamma$$

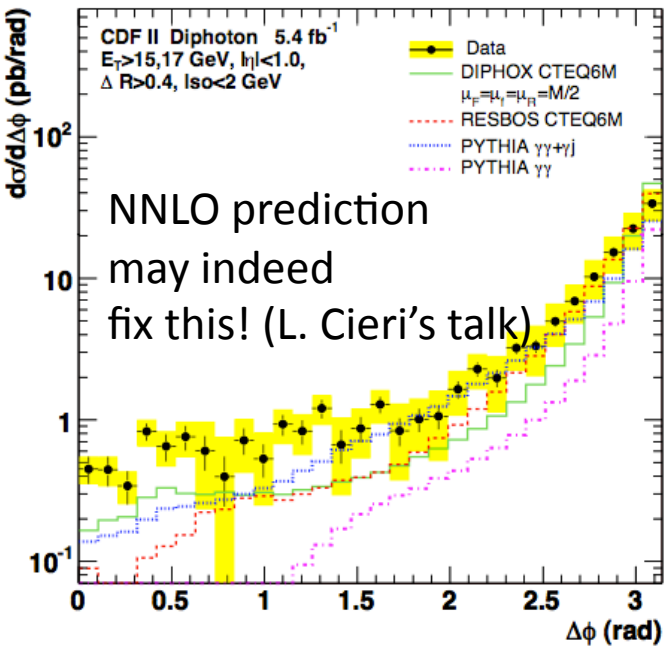
$$gg \rightarrow \gamma\gamma$$

+

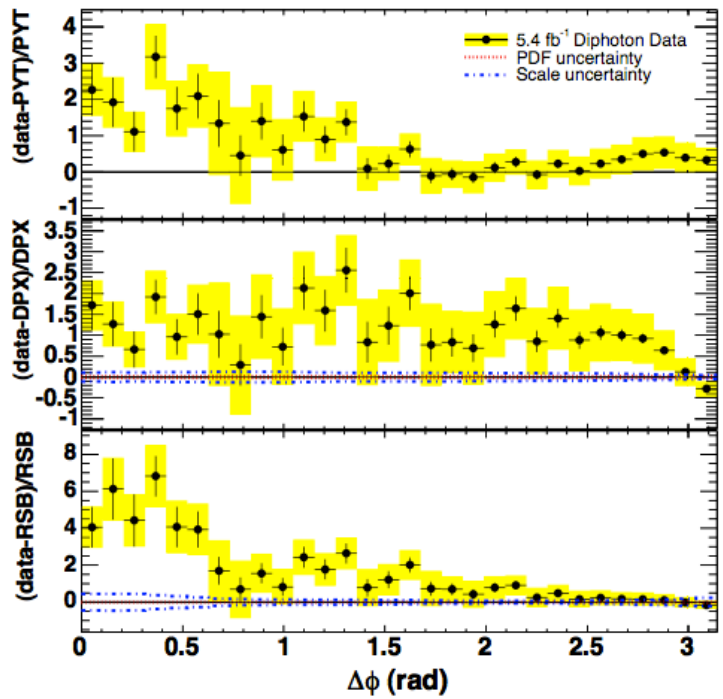
$$q\bar{q} \rightarrow g\gamma\gamma_{\mathrm{ISR}}$$

$$gq \rightarrow q\gamma\gamma_{\mathrm{ISR}}$$

$$gq \rightarrow q\gamma\gamma_{\mathrm{FSR}}$$

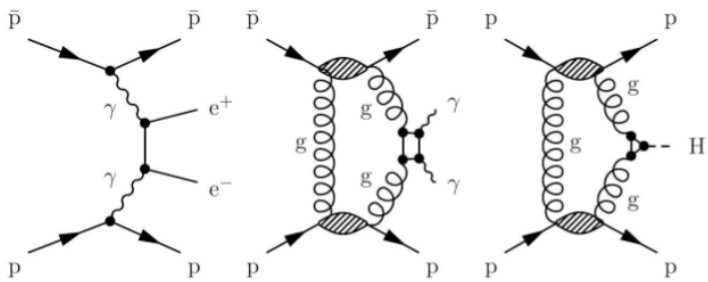


NNLO prediction
may indeed
fix this! (L. Cieri's talk)



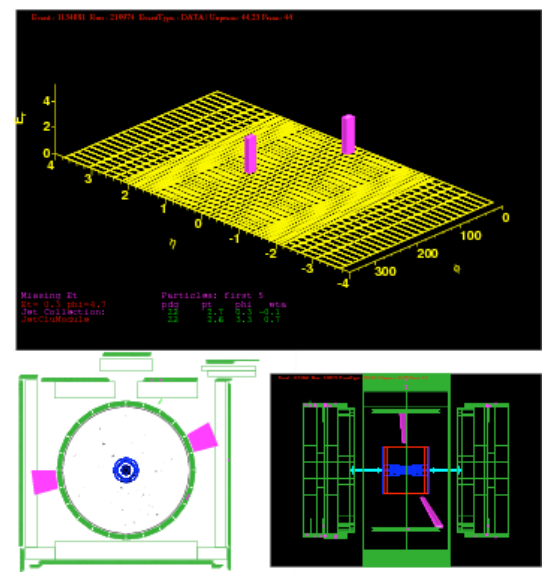
DIPHOX:
NLO calculation
with parton
fragmentation
into photons

Exclusive Diphoton Production with CDF



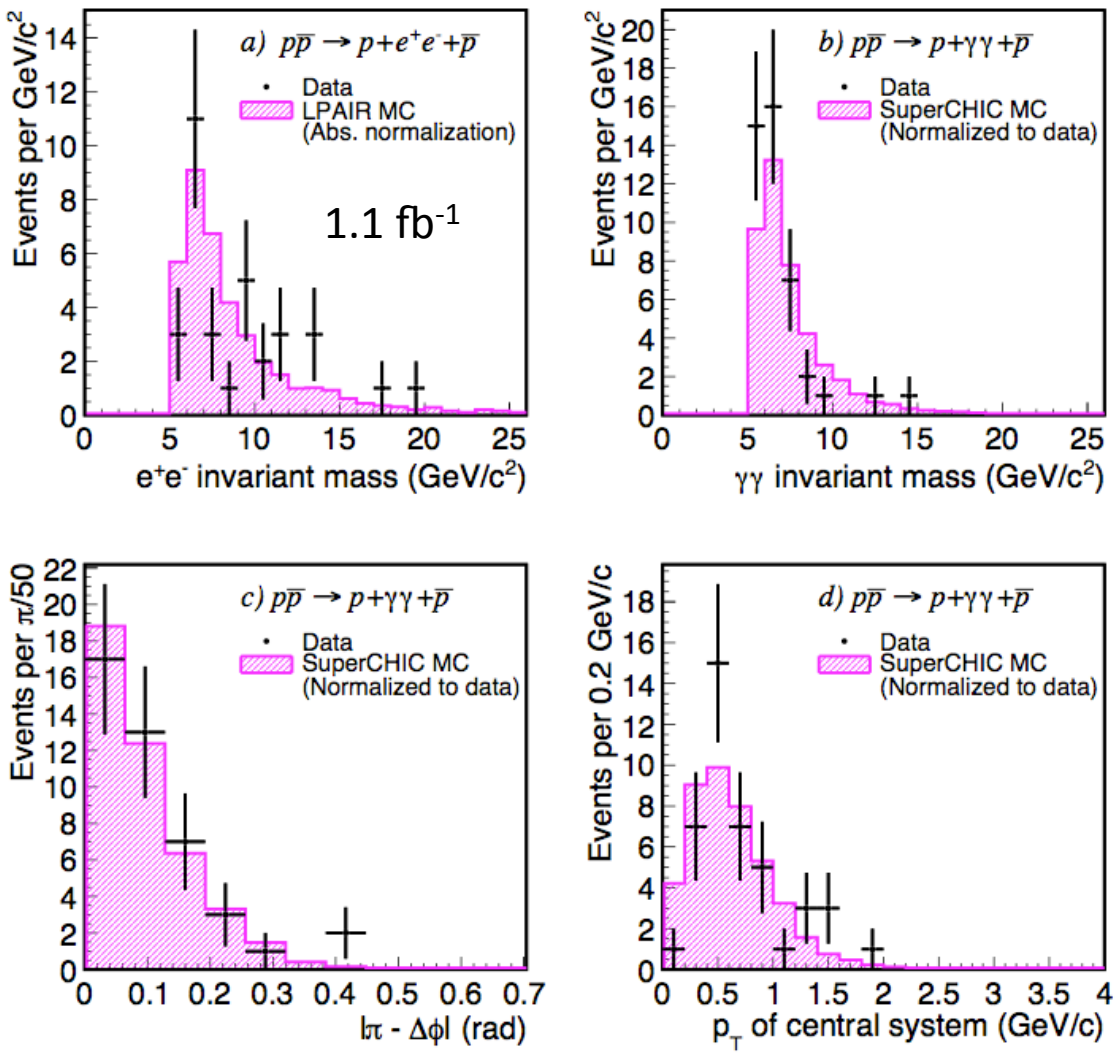
Integrated luminosity $\mathcal{L}_{\text{int}}$	1.11 ± 0.07 fb^{-1}
Exclusive efficiency	0.068 ± 0.004 (syst)
Exclusive $\gamma\gamma$	
Events	43
Photon pair efficiency	0.40 ± 0.02 (stat) ± 0.03 (syst)
Probability of no conversions	0.57 ± 0.06 (syst)
$\pi^0\pi^0$ b/g (events)	0.0, < 15 (95% C.L.)
Dissociation b/g (events)	0.14 ± 0.14 (syst)
Exclusive e^+e^-	
Events	34
Electron pair efficiency	0.33 ± 0.01 (stat) ± 0.02 (syst)
Probability of no radiation	0.42 ± 0.08 (syst)
Dissociation b/g (events)	3.8 ± 0.4 (stat) ± 0.9 (syst)

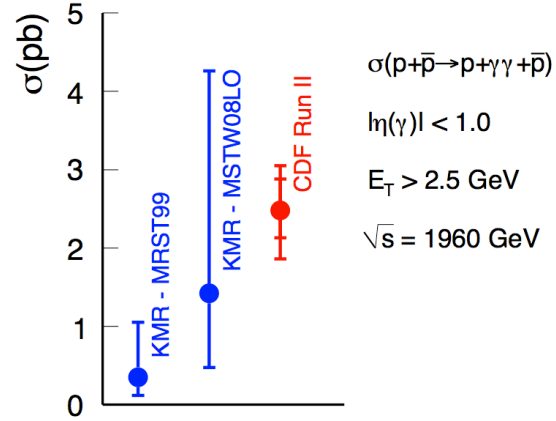
Select photon candidates with no track, $p_{T,\gamma}$>2.5 GeV, and |η|<1.0;
no other particles detected with |η|<7.4 (luminosity monitor and beam shower counters have to be empty to suppress dissociated proton background).
Also select exclusive e^+e^- Events



CDF Collaboration, arXiv:1112.0858 [hep-ex] (2011)

Exclusive Diphoton Production





$$\sigma_{p\bar{p}\to p\gamma\gamma\bar{p}} = 2.48^{+0.40}_{-0.35}(\text{stat})^{+0.40}_{-0.51}(\text{syst})\ \text{pb}$$

with

$$|\eta_\gamma| < 1.0 \text{ and } E_{T,\gamma} > 2.5\ \text{GeV}$$

And Electrons too

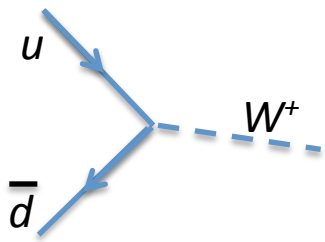
$$\sigma^{e^+e^-}_{exclusive} = 2.88^{+0.57}_{-0.48}(\text{stat}) \pm 0.63(\text{syst})\ \text{pb}$$

with

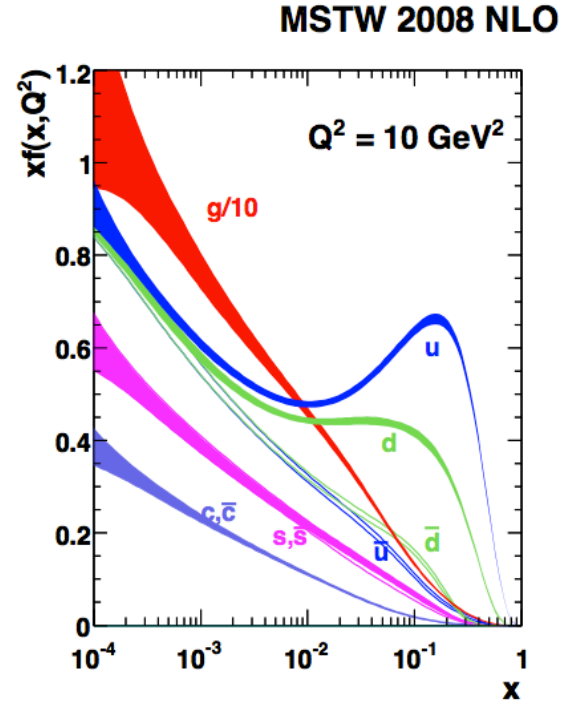
$$|\eta_e| < 1.0 \text{ and } E_{T,e} > 2.5\ \text{GeV}$$

compared with 3.25±0.07 (QED) (Vermaseren)

Measurement of the Forward-Backward Asymmetry of W Bosons with D0



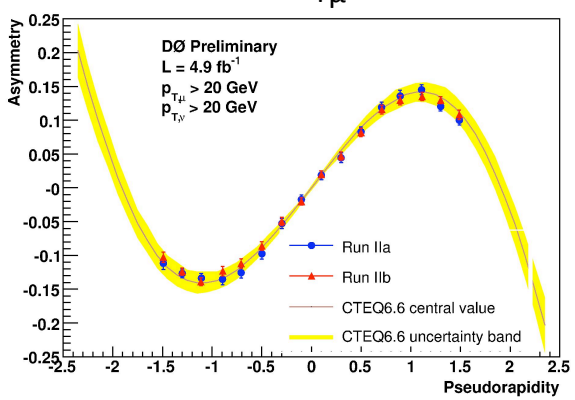
Forward-Backward Asymmetry comes largely from the difference between u and d PDF's.
The compton diagram gq→Wq also participates.



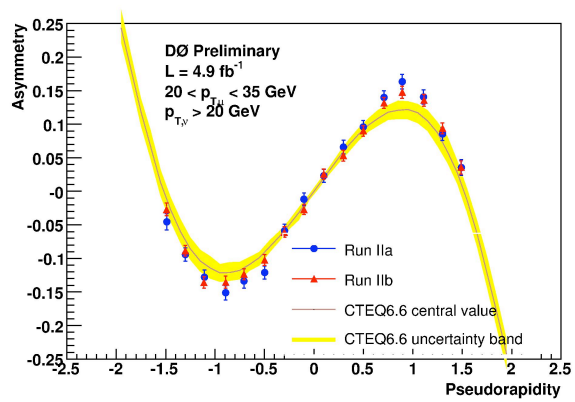
$$A(\eta) = \frac{1}{(1-2g)}\left[\frac{N^+(\eta) - N^-(\eta)}{N^+(\eta) + N^-(\eta)}\right]$$

Is the LEPTON asymmetry (directly observable. $p_{z,W}$ ambiguous due to neutrino solution.

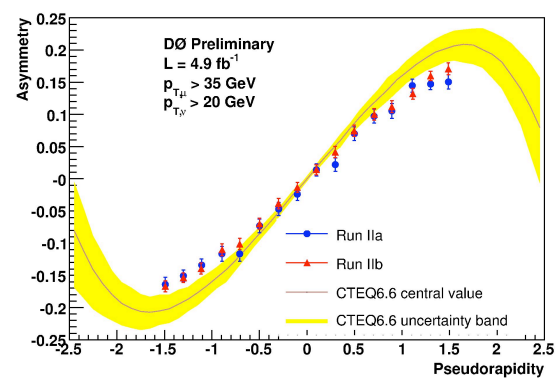
Inclusive $p_{T\mu}$>20 GeV



20 < $p_{T\mu}$ < 35 GeV



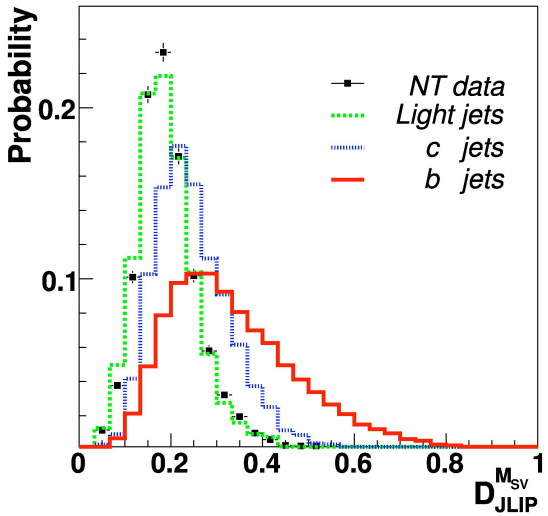
$p_{T\mu}$ > 35 GeV



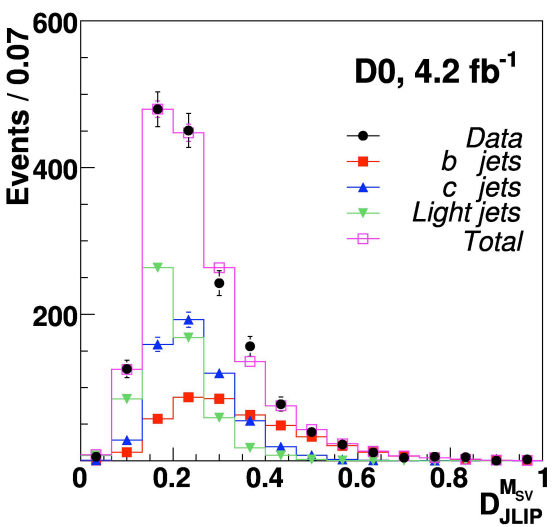
g accounts for the charge misidentification rate, determined with like-sign Z→μμ candidate events. Solenoid reversal results are consistent.

D0 Z + b jets

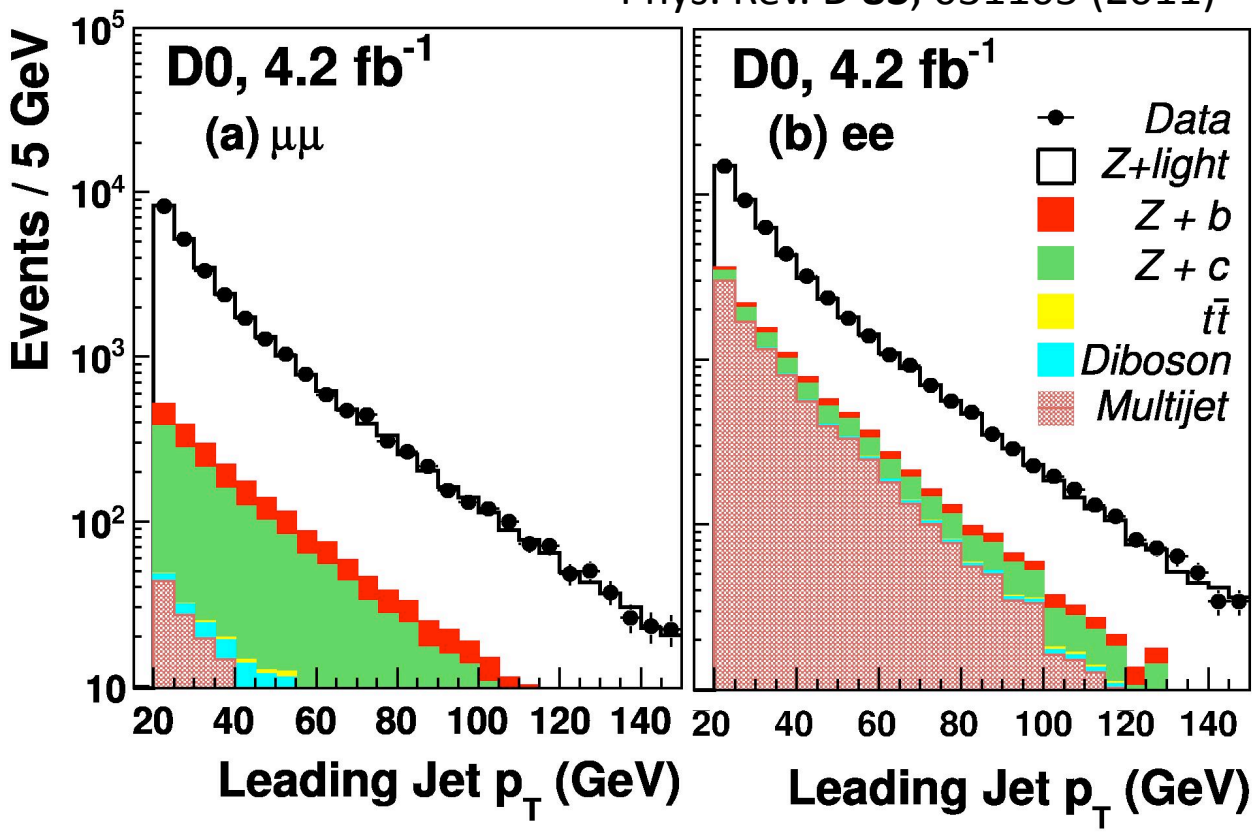
Phys. Rev. D **83**, 031105 (2011)



Vertex mass templates.
LF template validated with negative-tagged jets



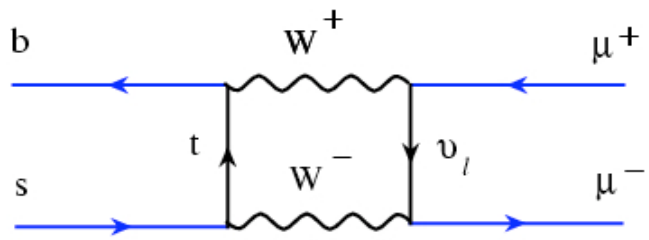
Fit to jets along with the Z

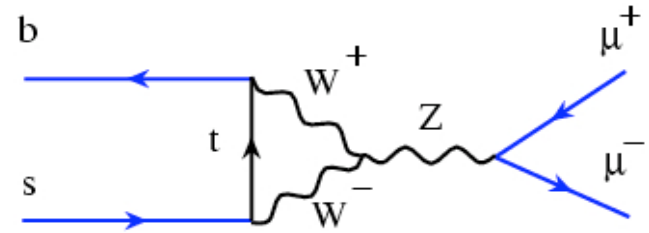


For events with a jet with p_T>20 GeV and $|\eta|$<2.5,
the ratio of $\sigma_{Z+b+X}/\sigma_{Z+jets}$= 0.0193 ± 0.0027
MCFM (NLO): $\sigma_{Z+b+X}/\sigma_{Z+jets}$= 0.0192 ± 0.0022
(3.6% less when detector response, resolution, hadronization, and underlying event are accounted for)

Search for B_s and $B_d \rightarrow \mu\mu$

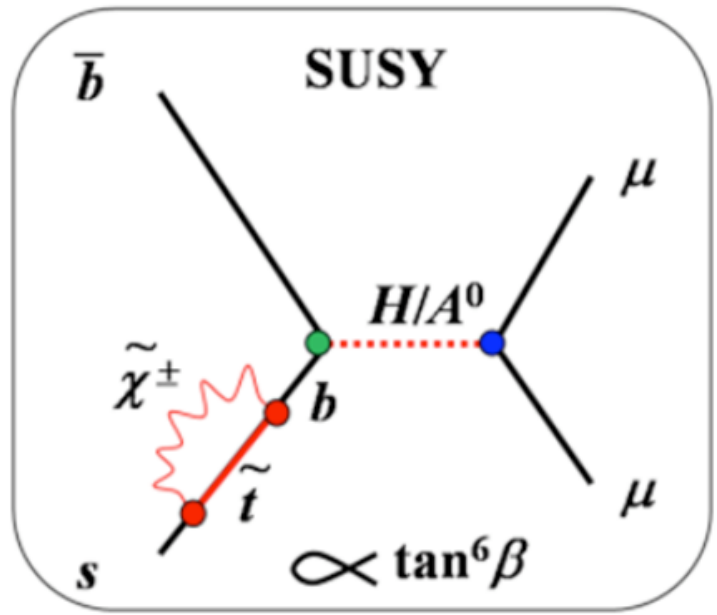
In the SM:





$Br(B_s \rightarrow \mu\mu)$ in the SM is ~10^{-9}

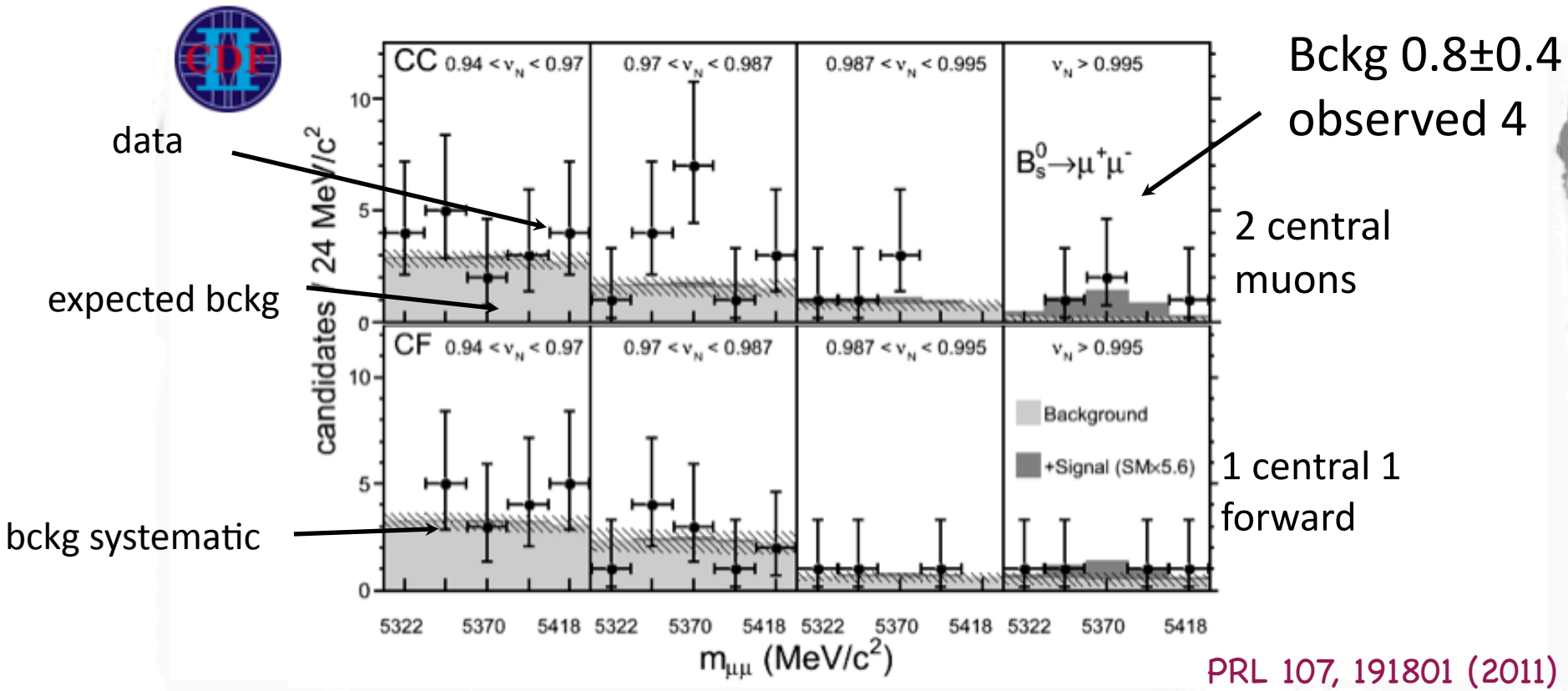
In many SUSY models, the branching ratio is enhanced by a few orders of magnitude



SUSY processes substitute $H^{\pm}$ for $W^{\pm}$ for example, and chargino/neutralino/squark loops

Z->h, A in the s-channel decay provides high sensitivity to tanβ

Latest $B_s \to \mu\mu$ result (CDF)



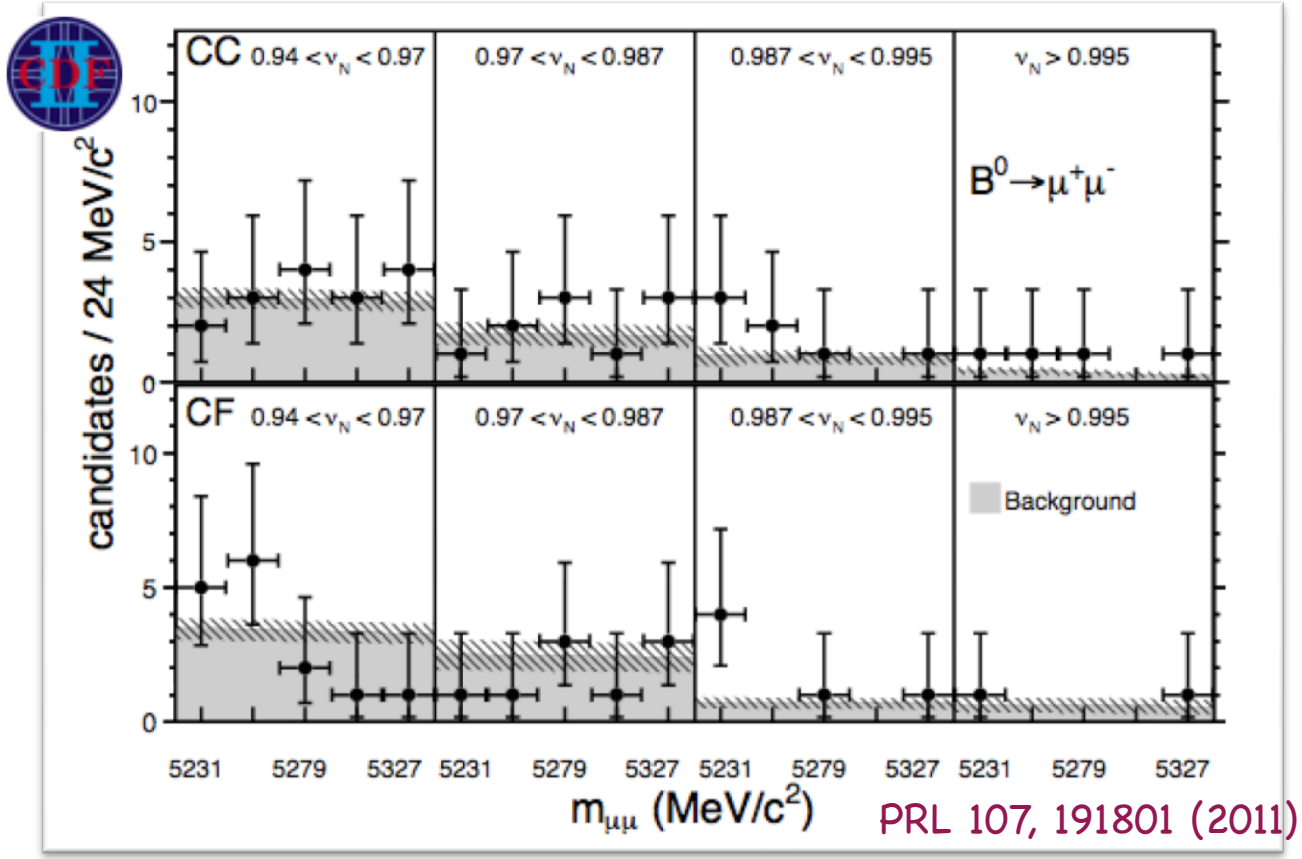
PRL 107, 191801 (2011)

Prob. that bckg (SM)produces >= fluctuation is 0.27% (1.9%)

$0.46\times10^{-8} < Br < 3.9\times10^{-8}$ at 90% CL ($Br = 1.8\,^{+1.1}_{-0.9}\times10^{-8}$)

A hint of a signal (not incompatible with latest LHC limits)

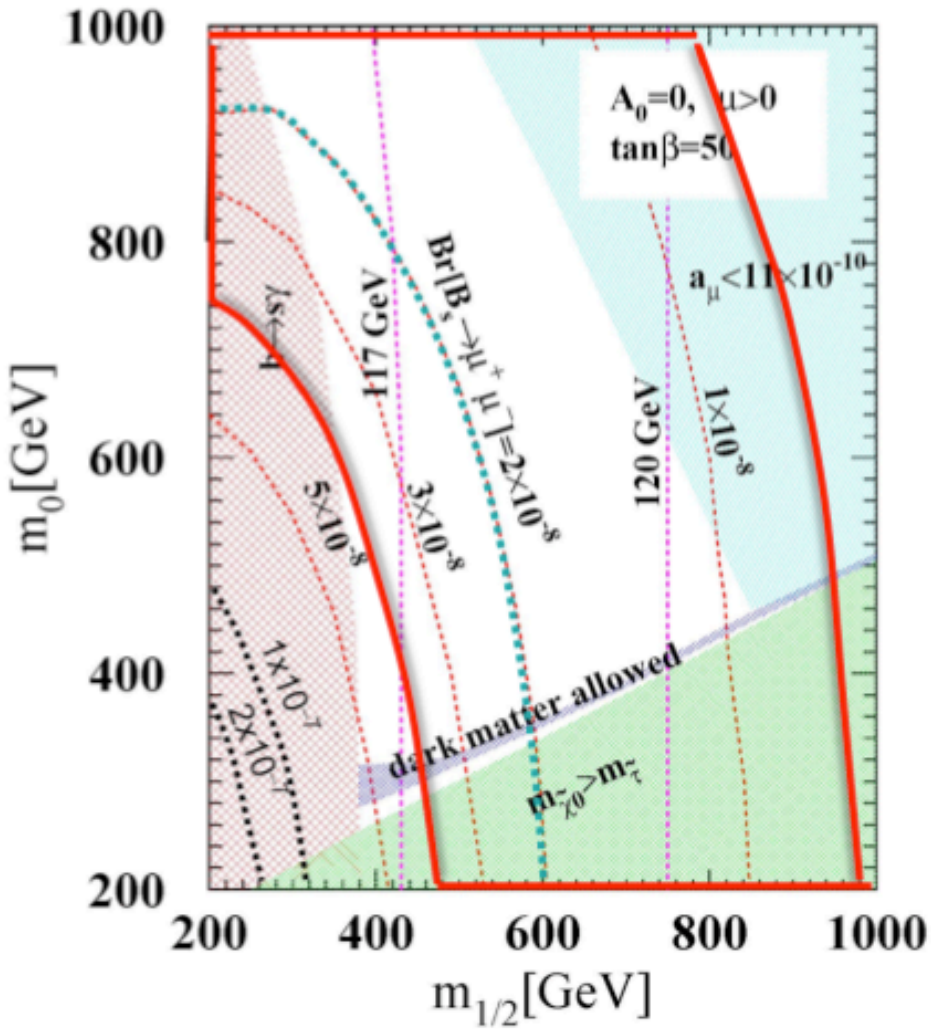
Also Search for $B^0 \to \mu\mu$



PRL 107, 191801 (2011)

Background hypothesis p-value = 0.23
BR< $6*10^{-9}$ @95%CL (expect 4.6)
Start to become interesting (60xSM)

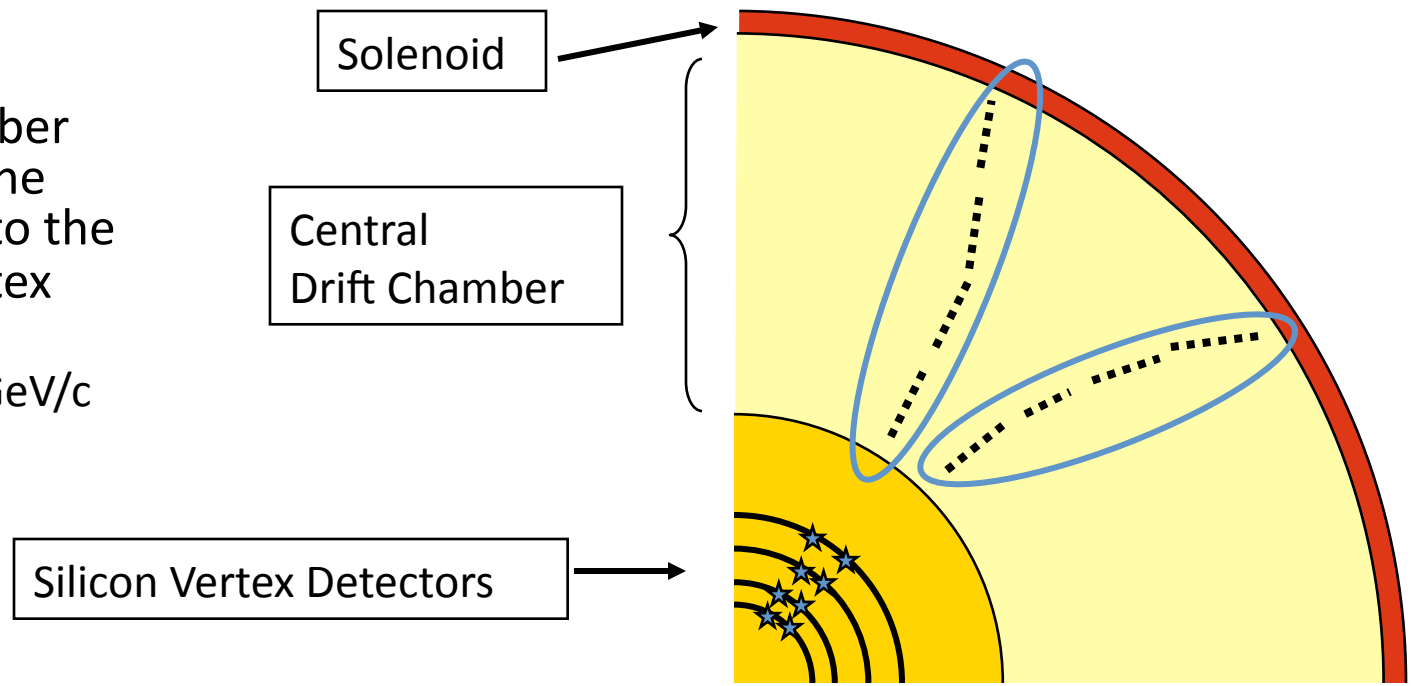
90 C.L. bounds on $B(B_s \to \mu^+\mu^-)$



$M_{\tilde{g}} \sim 1600$ GeV/c^2

CDF's Two-Track Trigger

- Drift chamber tracks define "roads" into the silicon vertex detector.
  - $p_T > 2$ GeV/c



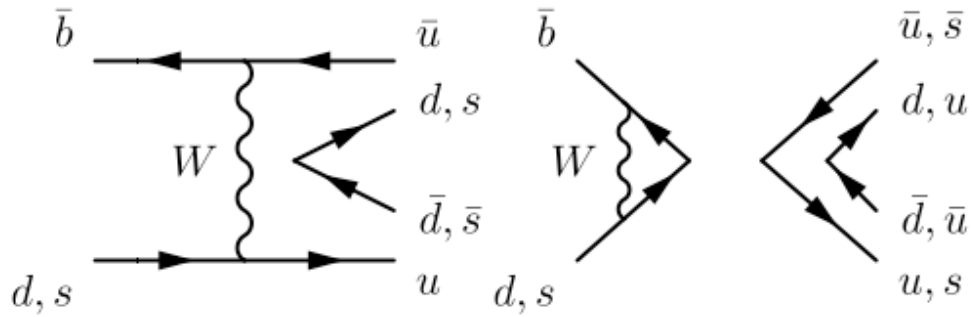
- Data that match prescribed patterns in the silicon triggers acceptance of the event.
- Provides purely hadronic final states - biased to heavy flavor
  - Flight from the beam > 200 μm

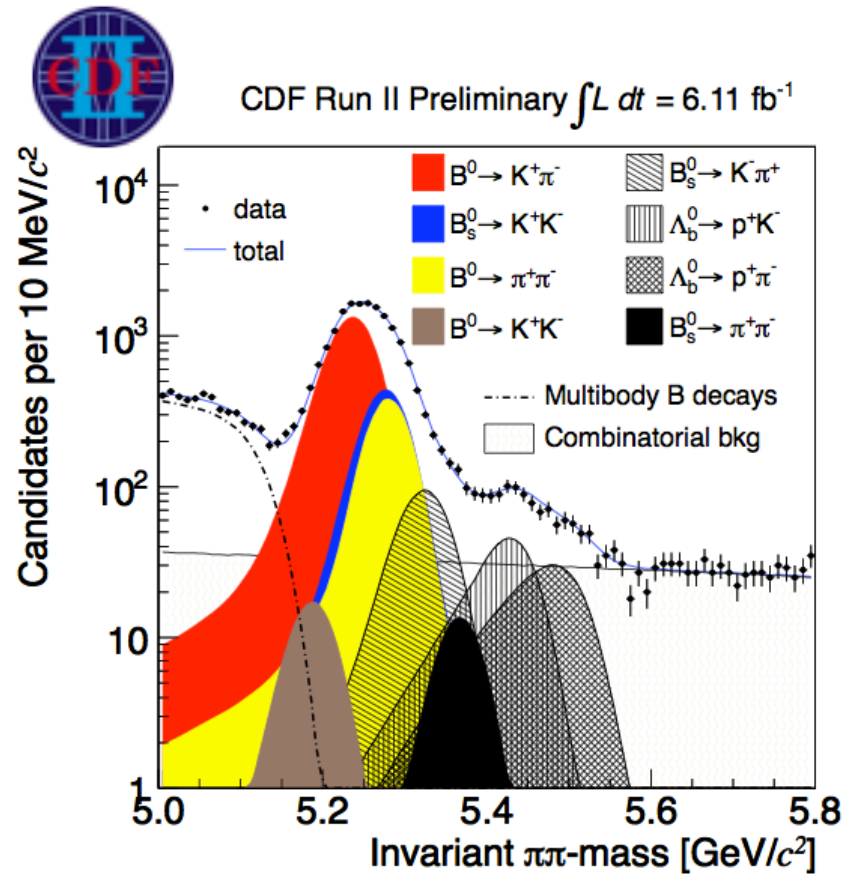
P. Lukens

Charmless two-body decays

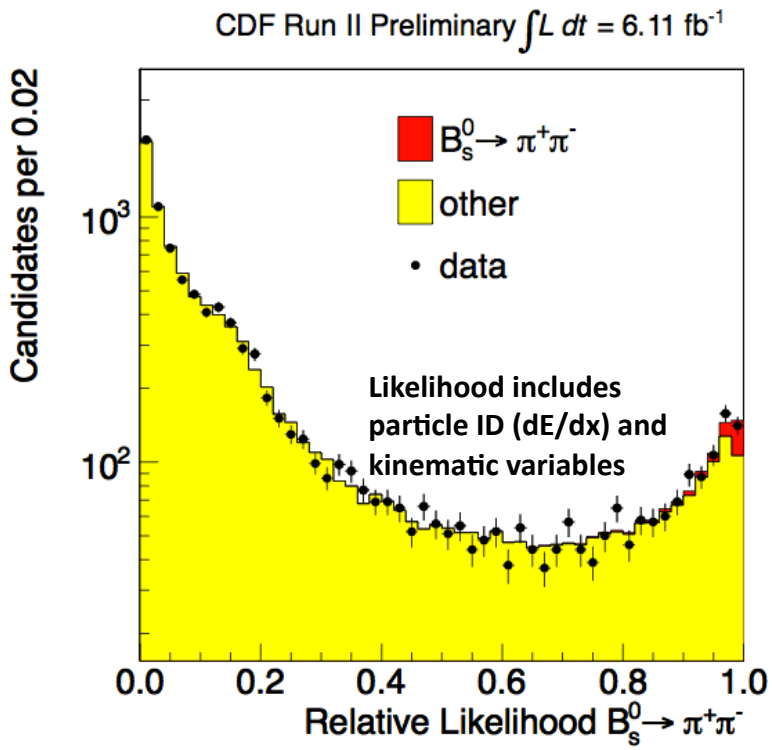
CDF pionereed the technique in hadron collisions and discovered several:

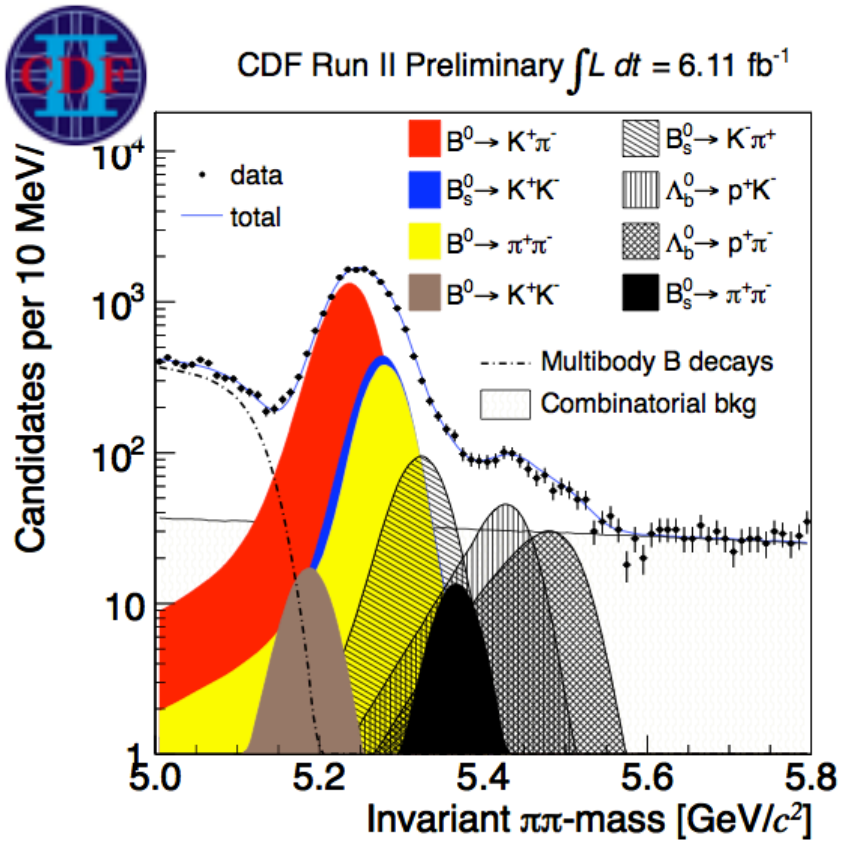
- First observations of:
  - $B_s \to K^+K^-$
  - $B_s \to K^+\pi^-$
  - $\Lambda_b \to p\pi^-$
  - $\Lambda_b \to pK^-$
- Measurements of
  - $A_{CP}(B_s \to K^+\pi^-)$
  - $A_{CP}(B^0 \to K^+\pi^-)$
  - $A_{CP}(\Lambda_b \to p\pi^-)$
  - $A_{CP}(\Lambda_b \to pK^-)$





Charmless two-body latest arrival: annihilation-type decays





- 3.7σ evidence for $B_s \to \pi\pi$.

BR = $(0.57 \pm 0.15 \pm 0.10)\times 10^{-6}$

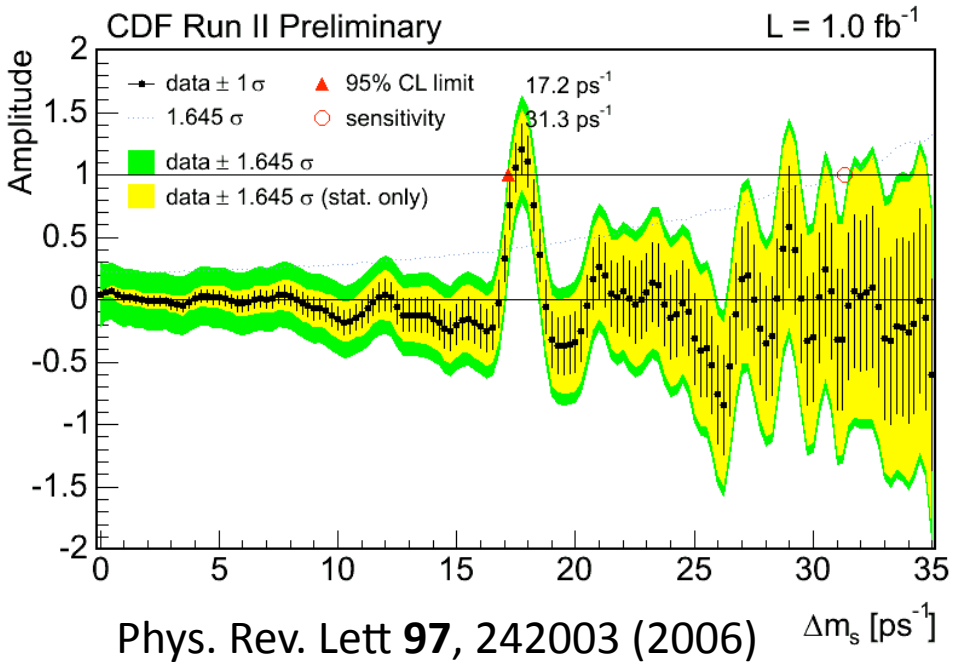
- 2-sided $B^0 \to KK$ bounds.

$0.05 < Br < 0.46 \times 10^{-6}$ at 90%CL

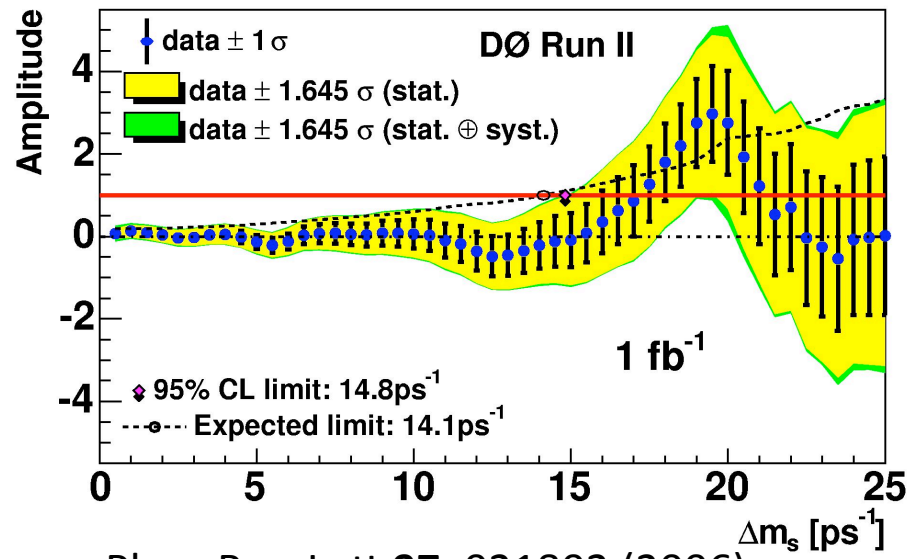
  - ➢Indicates strong annihilation
  - ➢Inportant input into models

arXiv:1111.0485 [hep-ex]

CDF and D0 Observed B_s Oscillations in 2006



Phys. Rev. Lett **97**, 242003 (2006)



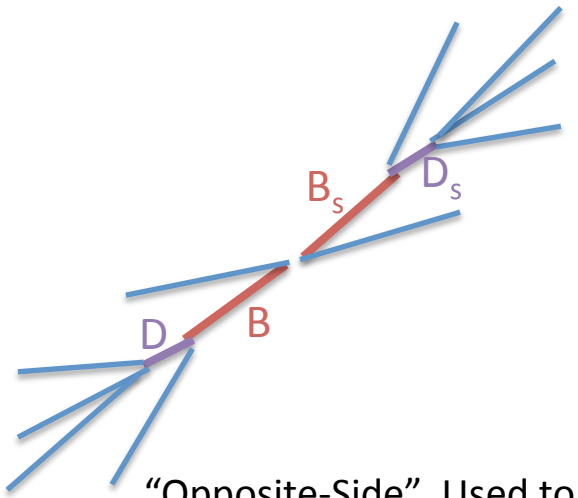
Phys. Rev. Lett **97**, 021802 (2006)

Ingredients: Measure sign at production: B_s or $\overline{B}_s$ next slide
sign at decay: use lepton charge in semileptonic deay
Proper time: Need momentum and decay length

LEP1 Couldn't do it – not enough resolution. Beam pipes were too big
Oscillation frequency is very high – several oscillations before decay.
SLD Couldn't do it – resolution is good, but not enough data

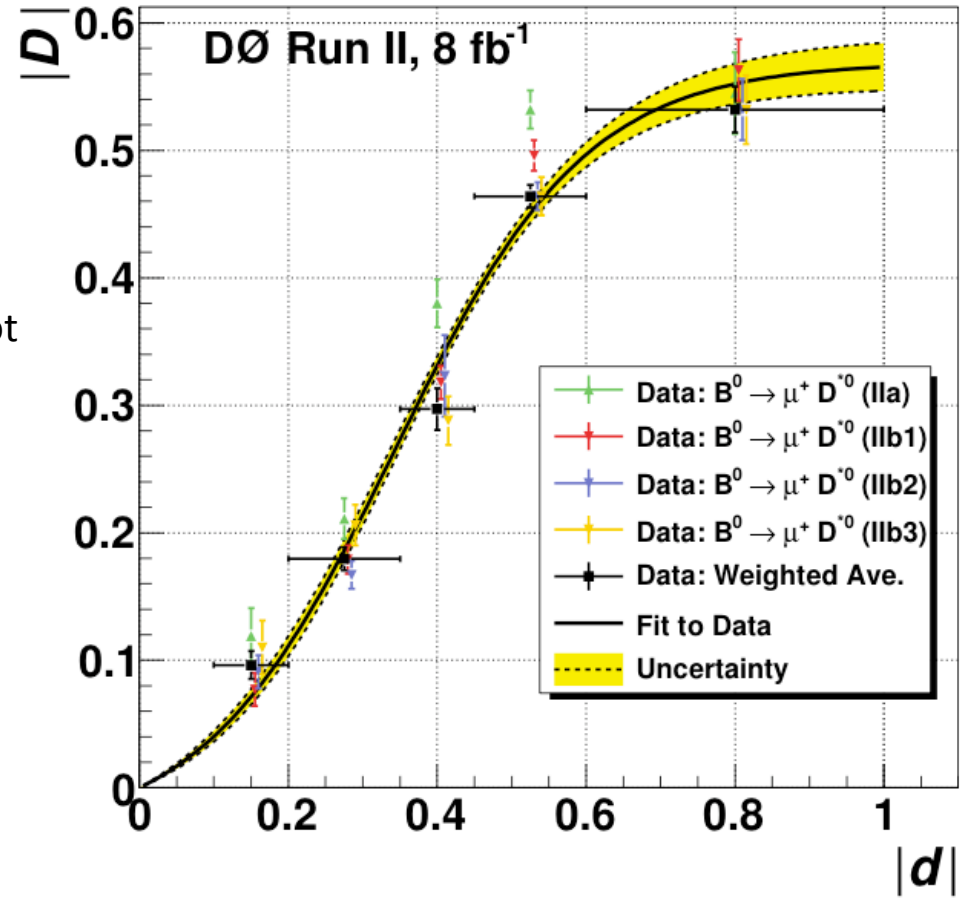
Opposite-Side Sign Identification Dilution Factor Calibration in Data

Need to identify the initial state as B_s or $\overline{B}_s$



Side used to measure B_s Mixing. Calibrations performed with B^0 decays and not B_s.

"Opposite-Side" Used to measure production sign of B
Ingredients to measured sign
Semileptonic decay lepton charge, or lacking that, vertex charge.
Continuous function d refers to how "sure" the measurement is (some events better determined than others)



The tagging dilution $\mathcal{D}$ is defined as

$$\mathcal{D} = \frac{N_{\rm cor} - N_{\rm wr}}{N_{\rm cor} + N_{\rm wr}},$$

CDF includes also "same-side" tagging information from signs of fragmentation tracks near the B_s candidate.

Characterization of the B_s System

In the neutral Kaon system, two bases: K^0 or $\overline{K}^0$ (strangeness)

K_L or K_S (CP)

K_L has a very much longer lifetime than K_s, and very slightly different masses. Different decays: K_L decays to 3π and K_s decays to 2π. CP violation discovered first in the neutral kaon system, with kaons of a characteristic lifetime decaying to the wrong CP eigenstate (K_L decaying to 2π about 1E-3 of the time)

Similar rich physics expected in the B_s system. The two states, B_L and B_H, are expected to be CP eigenstates.

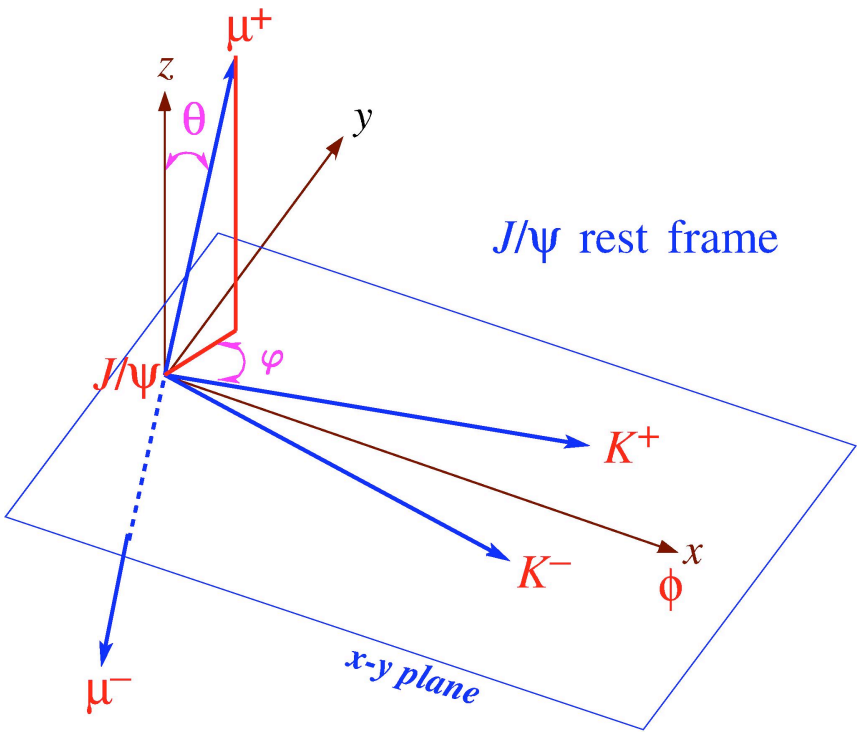
What is Δm_s? What is $\Delta\Gamma_s$? What is the CP-violating phase

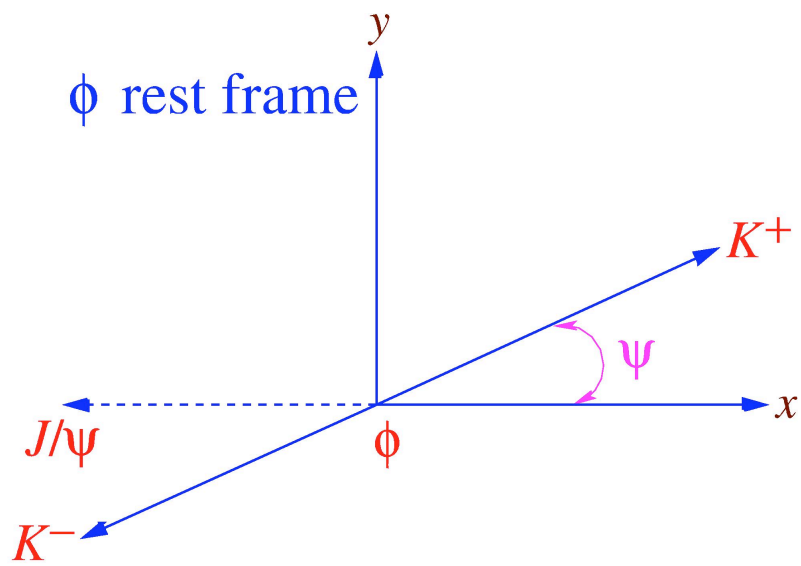
$$\phi_s^{J/\psi\phi} = -2\beta_s^{SM} = 2\arg[-V_{tb}V_{ts}^*/V_{cb}V_{cs}^*] = -0.038 \pm 0.002 \text{ in the SM}$$

Strategy: Use $B_s \rightarrow J/\psi\ \phi$ decays. Accessible from unmixed decays and mixed decays. Interference between $B_s \rightarrow J/\psi\ \phi$ and $B_s \rightarrow \overline{B}_s \rightarrow J/\psi\ \phi$

Angular distributions of $J/\psi \rightarrow \mu^+\mu^-$ and $\phi \rightarrow K^+K^-$ to separate out the CP-even and CP-odd components as functions of proper time.

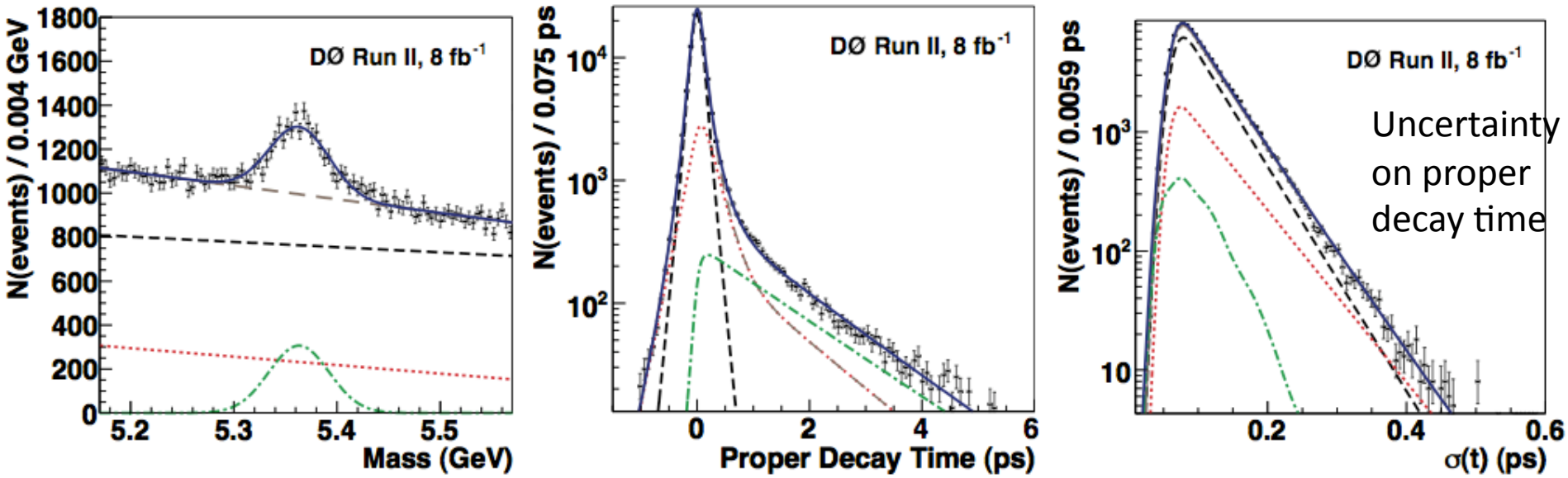
Reconstruction of $B_s \rightarrow J/\psi\ \phi \rightarrow \mu^+\mu^-\ K^+K^-$





Defined angles shown in pink

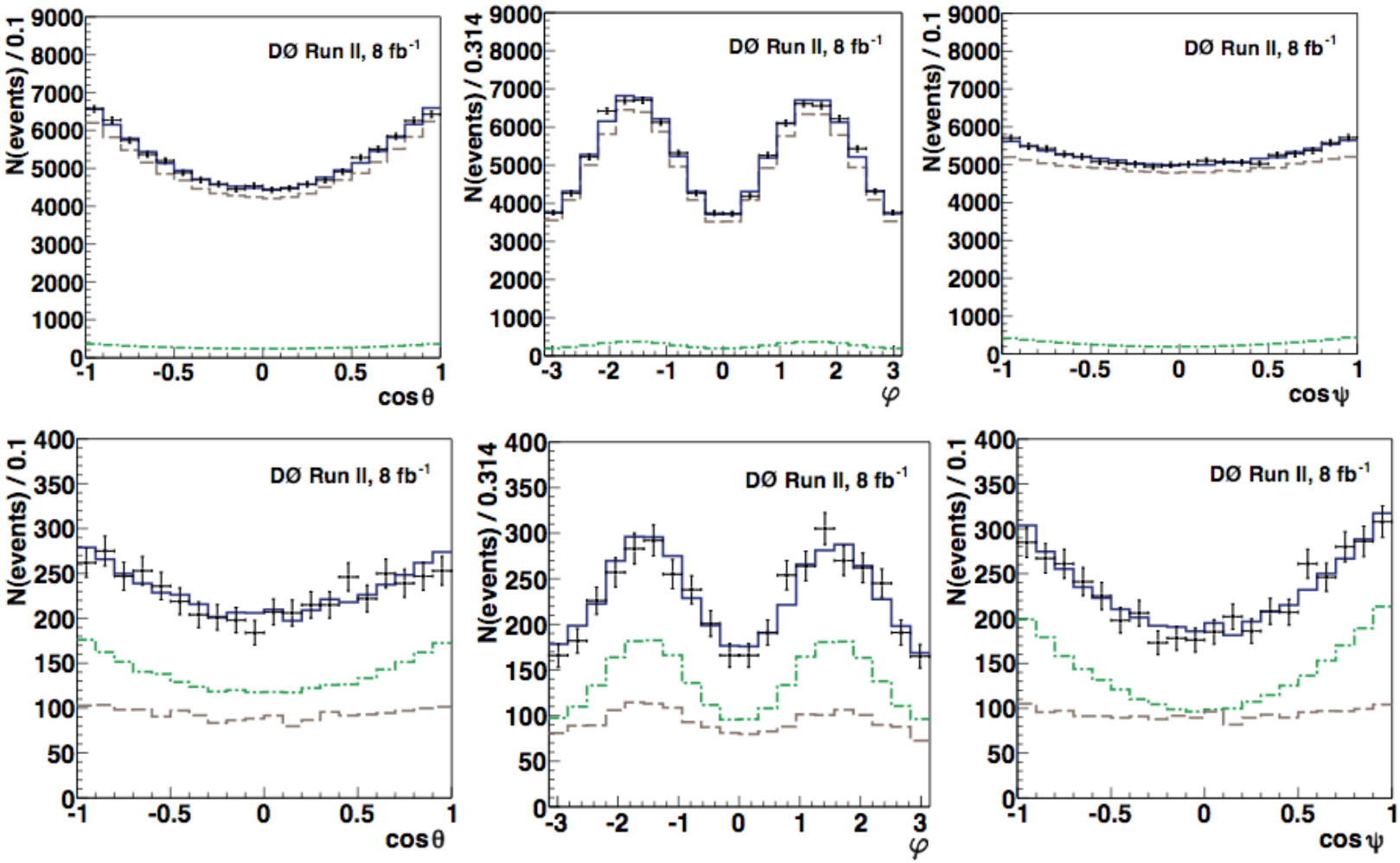
Coping with Backgrounds to $B_s \rightarrow J/\psi\ \phi \rightarrow \mu^+\mu^-\ K^+K^-$



Sidebands characterize rate and angular distributions of combinatoric background.

Reconstructed Angular Distributions in $B_s \rightarrow J/\psi\ \phi \rightarrow \mu^+\mu^-\ K^+K^-$

Green: B_s signal. Gray: Combinatoric Background Black: total



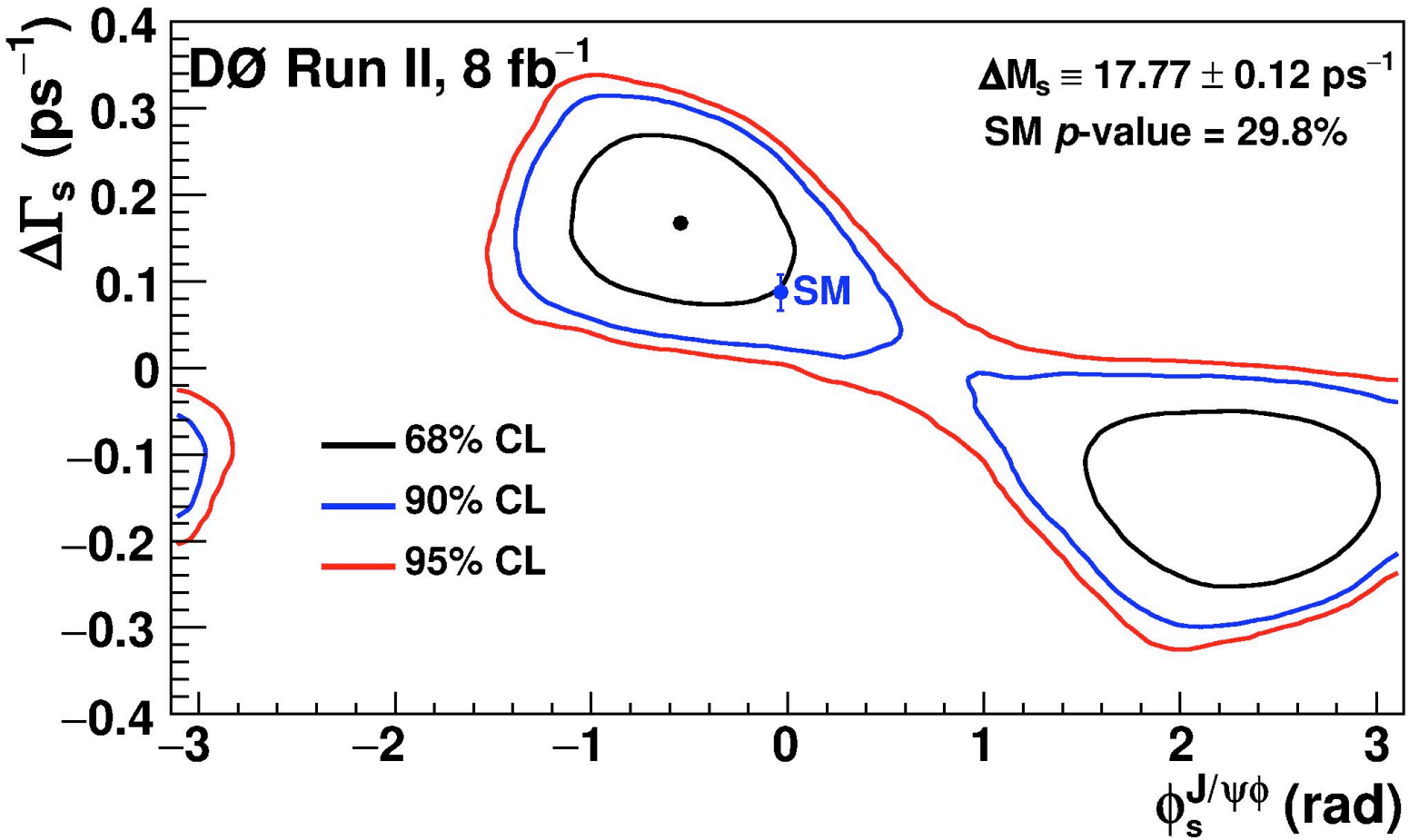
Background rich sidebands

Signal region

Best fit functions shown

These are made in bins of proper decay time too.

Constraints on $\Delta\Gamma_s$ and the CP-Violating Phase $\phi_s^{J/\psi\phi}$



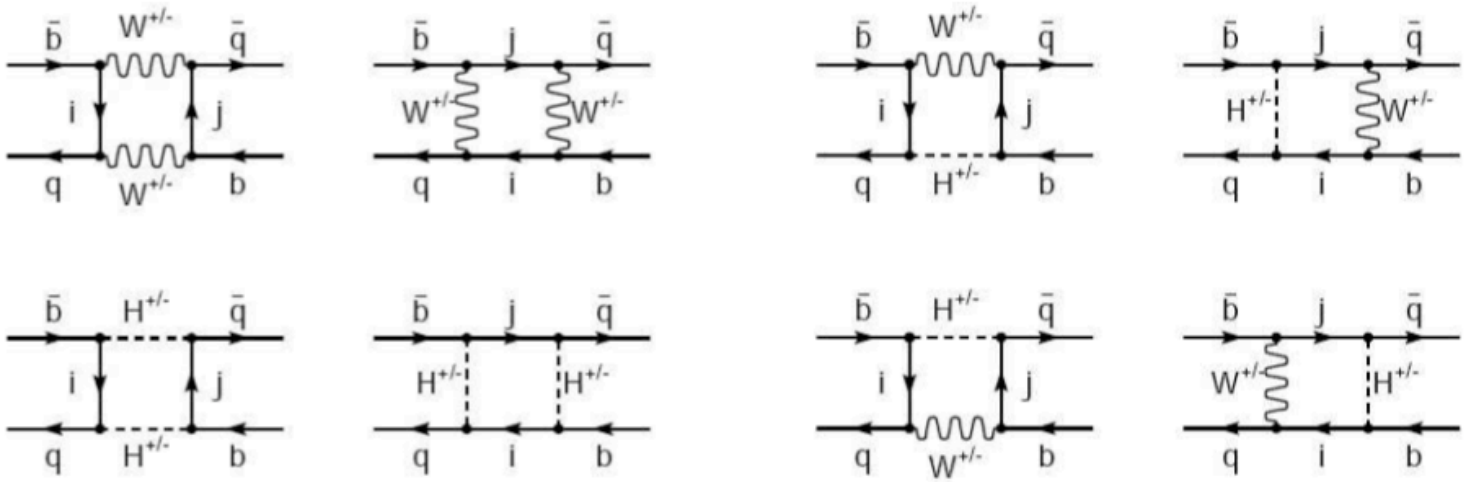
D0 Collaboration, arXiv:1109.3166v1

Measurement of the Like-Sign Dimuon CP-Violating Asymmetry

Look in the data for events with $\mu^+\mu^+$ and $\mu^-\mu^-$.

Like-sign dimuons come from

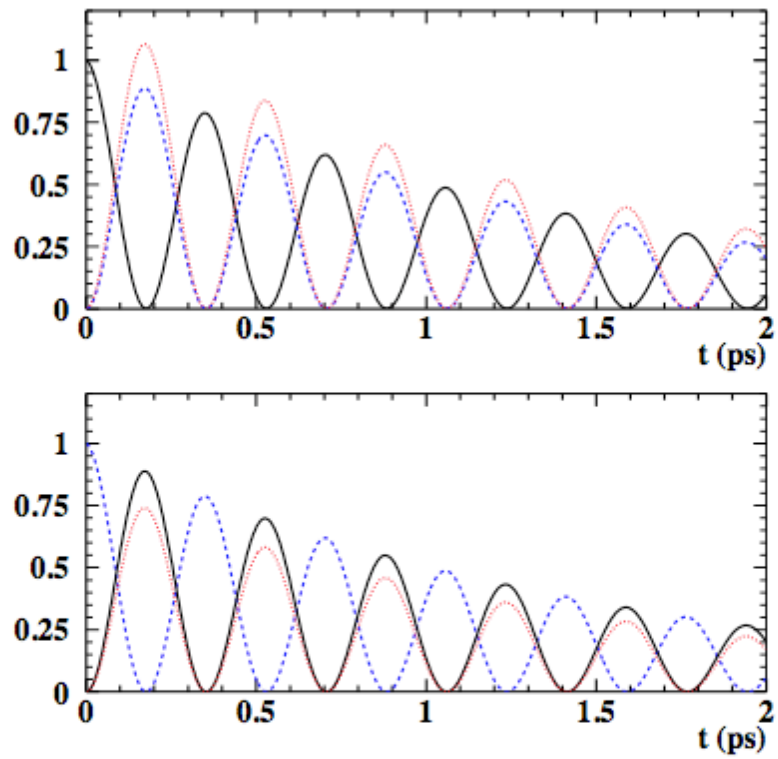
- B hadron mixing
- D hadron mixing (which is very small)
- Multi-heavy-flavor production/multiple semileptonic decay
- Fake muons



$B_q^0 \leftrightarrow \bar{B}_q^0$ mixing is sensitive to new physics. $q = d, s$.

B_s Oscillations with and Without CP violation

B^0=bd meson,
has a slightly longer lifetime and a *much* longer oscillation period



Top: Histogram of proper time of decays $B_s^0 \to \mu^+ X$ (continuous line), $B_s^0 \to \bar{B}_s^0 \to \mu^- X$ (dashed line if no CP violation, dotted red line if CP violation). Bottom: The same for $\bar{B}_s^0$ at $t = 0$.

slide courtesy Bruce Hoeneisen

CP-violating asymmetry from semileptonic B decays

$$A^b_{\mathsf{sl}} \equiv \frac{N^{++}_{b\bar{b}} - N^{--}_{b\bar{b}}}{N^{++}_{b\bar{b}} + N^{--}_{b\bar{b}}},$$

Contributions from B^0 and B_s:

$$A^b_{\mathsf{sl}} = C_d a^d_{\mathsf{sl}} + C_s a^s_{\mathsf{sl}},$$

$$a^q_{\mathsf{sl}} = \frac{\Delta\Gamma_q}{\Delta M_q} \tan\phi_q, \text{ with } q = d, s.$$

A^b_{sl} is obtained from the "raw" charge asymmetries

$$a \equiv \frac{n^+ - n^-}{n^+ + n^-}, \text{ and } A \equiv \frac{N^{++} - N^{--}}{N^{++} + N^{--}}.$$

In the Standard Model $A^b_{\mathsf{sl}} = (-0.028^{+0.005}_{-0.006})\% \approx 0.$

Deviations from the SM prediction are signs of CP-violating new physics

Three methods to measure A^b_{sl}: $(a_S \equiv c_b A^b_{\mathsf{sl}},\ A_S \equiv C_b A^b_{\mathsf{sl}})$:

Inclusive muon sample (1 μ):

$$a \equiv \frac{n^+ - n^-}{n^+ + n^-} = \sum_{i=0}^{5} f^i_\mu \{ f^i_S (a_S + \delta_i) + f^i_K a^i_K + f^i_\pi a^i_\pi + f^i_p a^i_p \}.$$

Like-sign dimuon sample (2 μ):

$$\begin{aligned} A &\equiv \frac{N^{++} - N^{--}}{N^{++} + N^{--}} \\ &= F_{SS} A_S + F_{SL} a_S + \sum_{i=0}^{5} F^i_\mu \{ (2 - F^i_{\mathsf{bkg}}) \delta_i \\ &\quad + F^i_K a^i_K + F^i_\pi a^i_\pi + F^i_p a^i_p \}. \end{aligned}$$

Combined: $A - \alpha a$. α chosen to minimize total uncertainty.

slide courtesy Bruce Hoeneisen

i indexes momentum bin

Muon p_T range (GeV)
$1.5 - 2.5$
$2.5 - 4.2$
$4.2 - 5.6$
$5.6 - 7.0$
$7.0 - 10.0$
$10.0 - 25.0$

All parameters are measured with data as a function of p_T by reconstructing exclusive decays:

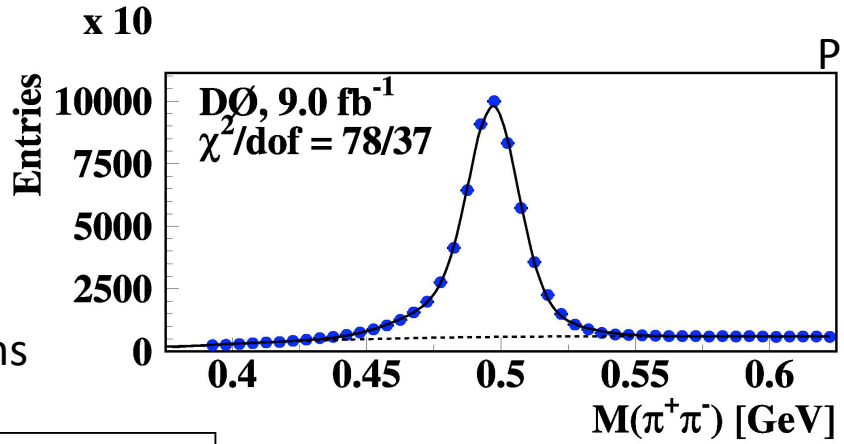
- f_K: $K^{*+} \to K_S\pi^+$, $K^{*0} \to \pi^- K^+ \to \mu^+$ and $K_S \to \pi^+\pi^- \to \mu$.
- f_π: f_K, $K_S \to \pi^+\pi^- \to \mu$, $\phi \to K^+K^- \to \mu$ and n_π/n_K from MC.
- f_p: f_K, $\Lambda \to \pi^- p^+ \to \mu$, $\phi \to K^+K^- \to \mu$ and n_p/n_K from MC.
- a_K: $K^{*0} \to \pi^- K^+ \to \mu^+$ and $\phi \to K^+K^- \to \mu$.
- a_π: $K_S \to \pi^+\pi^- \to \mu$.
- a_p: $\Lambda \to \pi^- p \to \mu$.
- δ: $J/\psi \to$ track track $\to \mu$.
- $R_K \equiv F_K/f_K$: $K^{*0} \to \pi^- K^+ \to \mu^+$ (null-fit method) and $K_S \to \pi^+\pi^- \to \mu$.

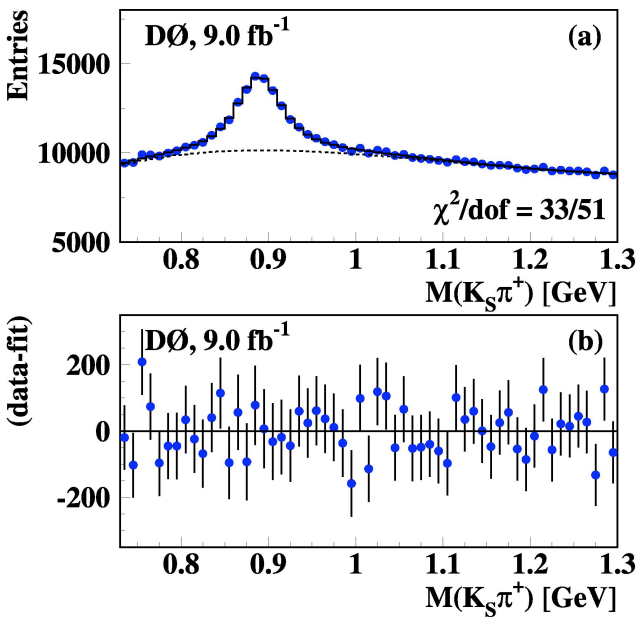
slide courtesy Bruce Hoeneisen

Measurement of the Like-Sign Dimuon CP-Violating Asymmetry

Phys. Rev. D **84**, 052007 (2011)

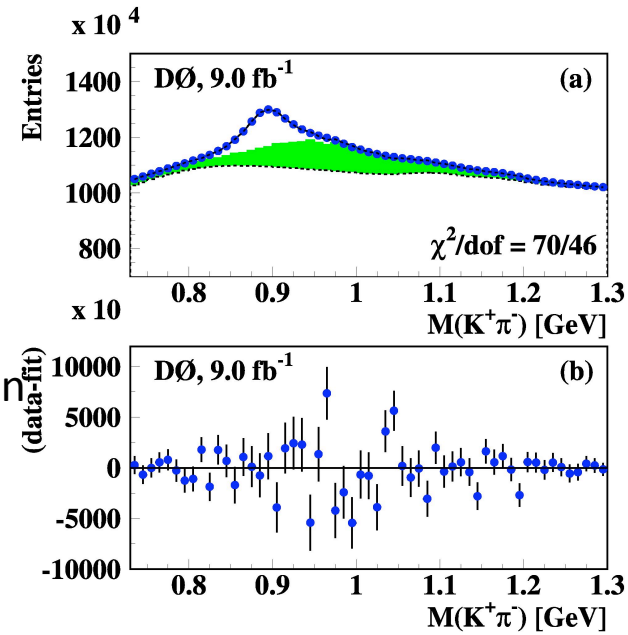
K_{short} peak – pure sample of charged pions. Used to calibrate fake rate for pions identified as muons



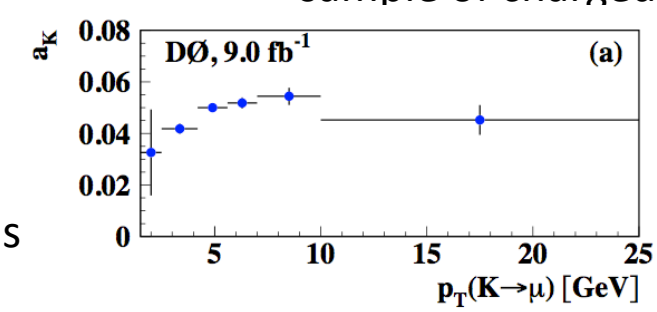


Dashed lines: Combinatorial background

Green: Contribution from $\rho^0 \rightarrow \pi^+\pi^-$ decays



K* reconstruction for a sample of charged kaons

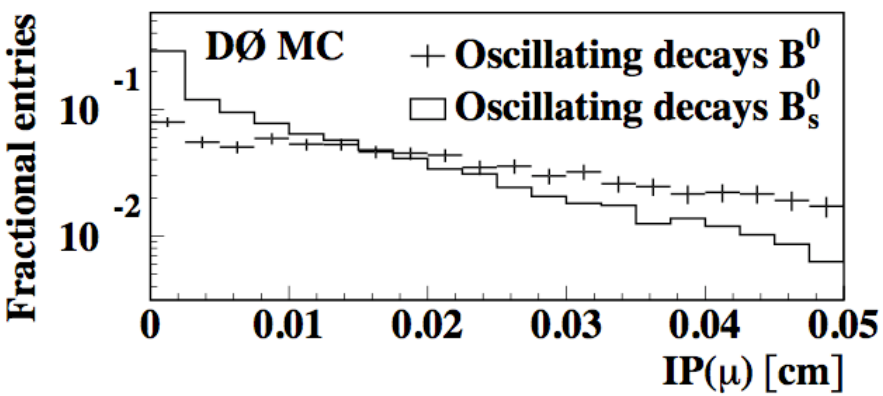


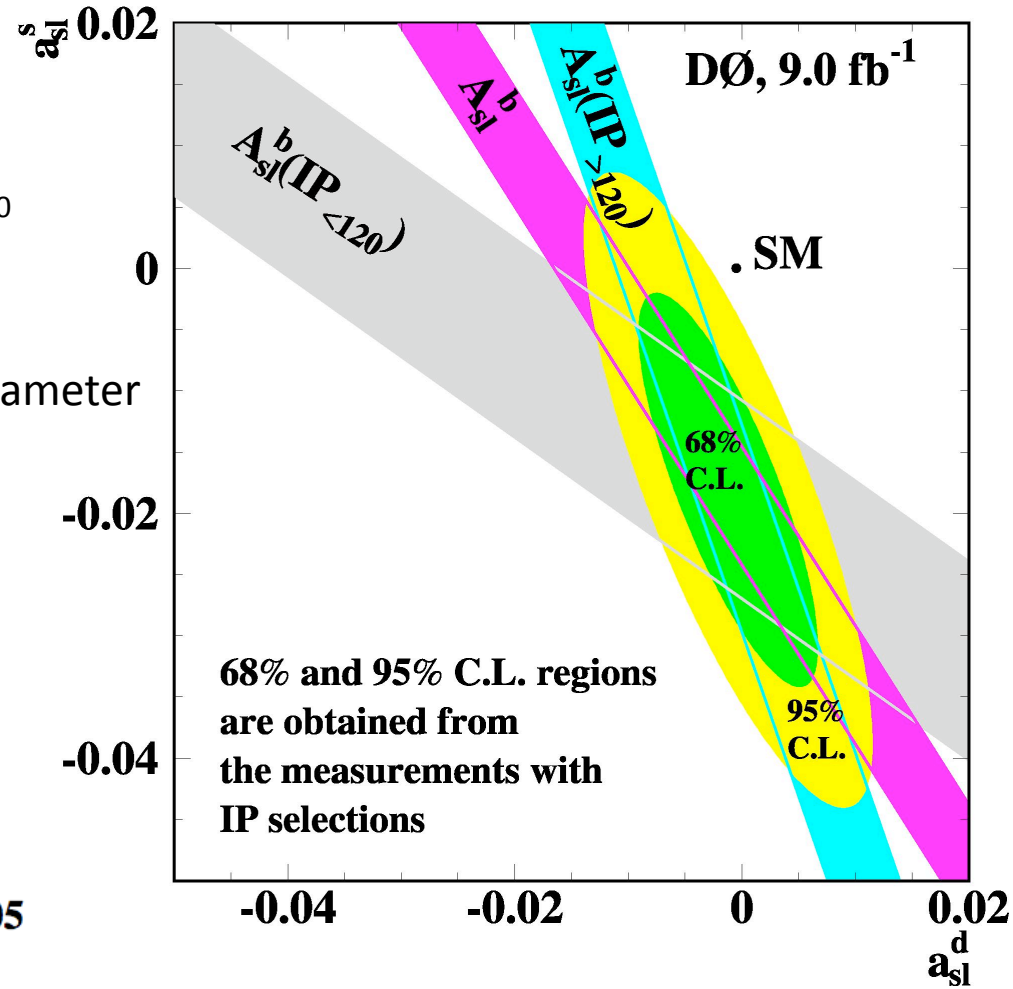
Data used to measure both background rates and asymmetries. The Kaon asymmetry is the largest due to the different interaction lengths for K^+ and K^- in detector material.

Measurement of the Like-Sign Dimuon CP-Violating Asymmetry Separately for the B_s and the B^0

Very different mixing frequencies allow separation of how much of the CP-violating asymmetry comes from B^0 and B_s decays.

Sample separated into low-impact-parameter and high-impact-parameter subsets and interpreted jointly.



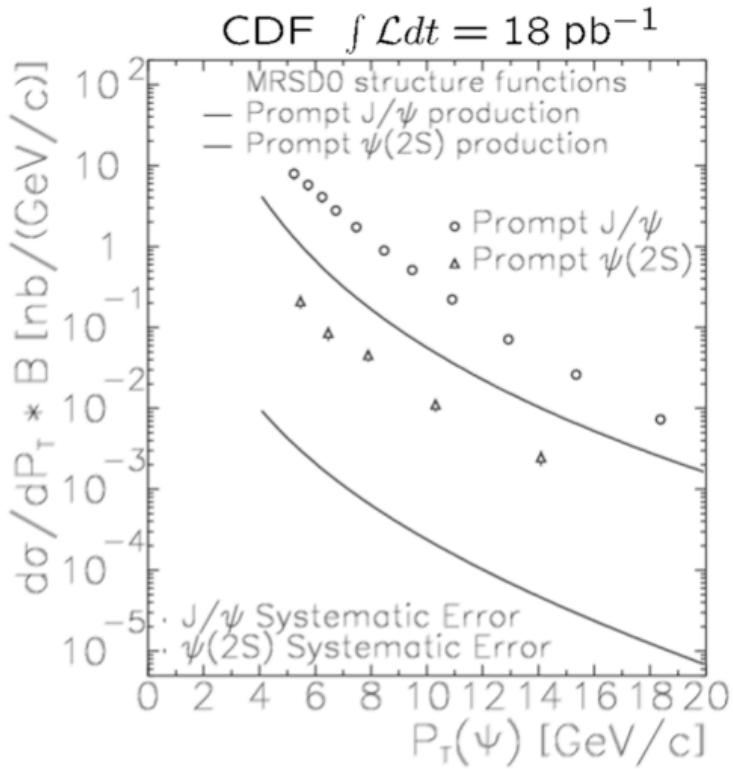


D0 Collaboration, Phys. Rev. D 84, 052007 (2011)

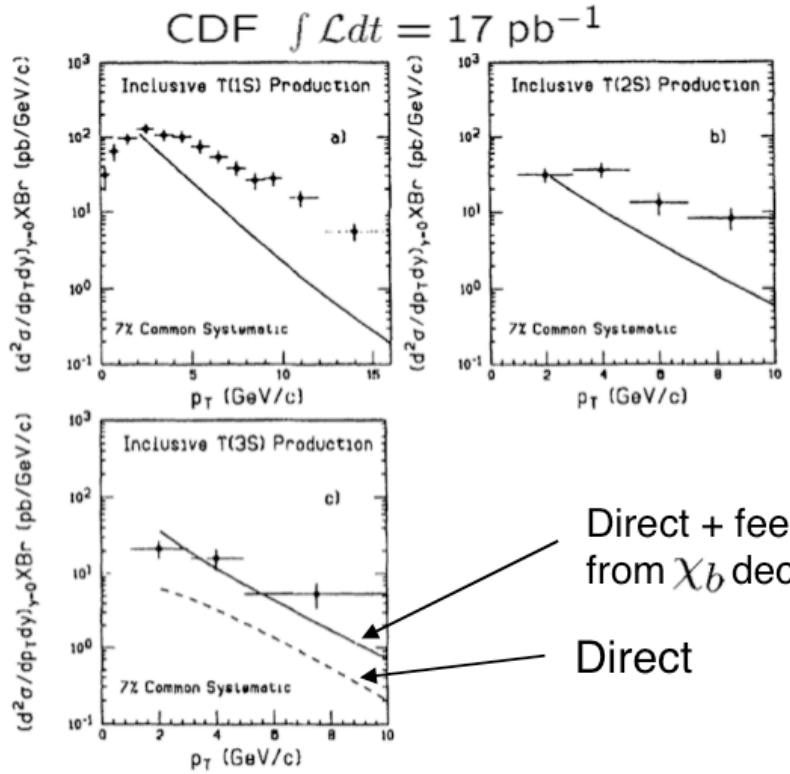
Upsilon Polarization Measurement Motivation

Old problems predicting J/ψ and ϒ Production (much better now)

Phys. Rev. Lett. 79, 572 (1997)



Phys. Rev. Lett. **75**, 4358 (1995)



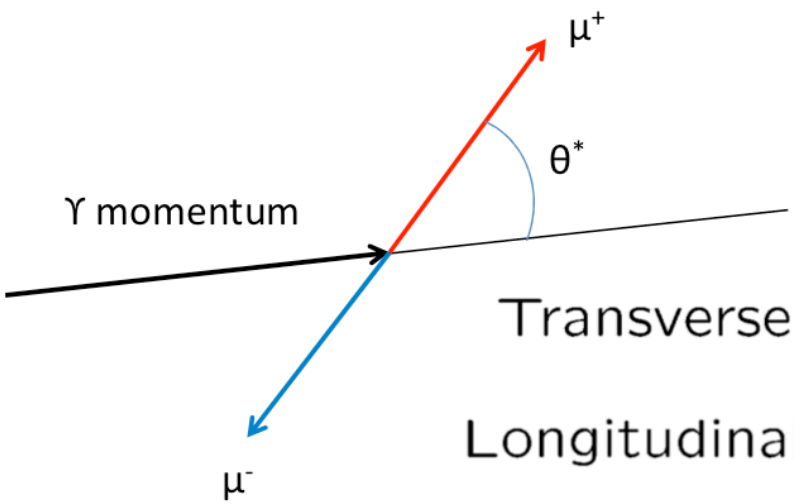
- Prompt J/ψ and ϒ cross sections much larger than expected…
  - ↳ color-singlet vs color-octet production mechanisms
    - ↳ ***Polarization measurements***

slide courtesy M. Jones

Upsilon "Polarization"

slide courtesy M. Jones

- A better term is *spin alignment…*
  - *Transverse* polarization: $|J,\lambda\rangle = |1,\pm 1\rangle$
  - *Longitudinal* polarization: $|J,\lambda\rangle = |1,0\rangle$



$$\frac{d\sigma}{d\cos\theta^*} \sim 1 + \alpha\cos^2\theta^*$$

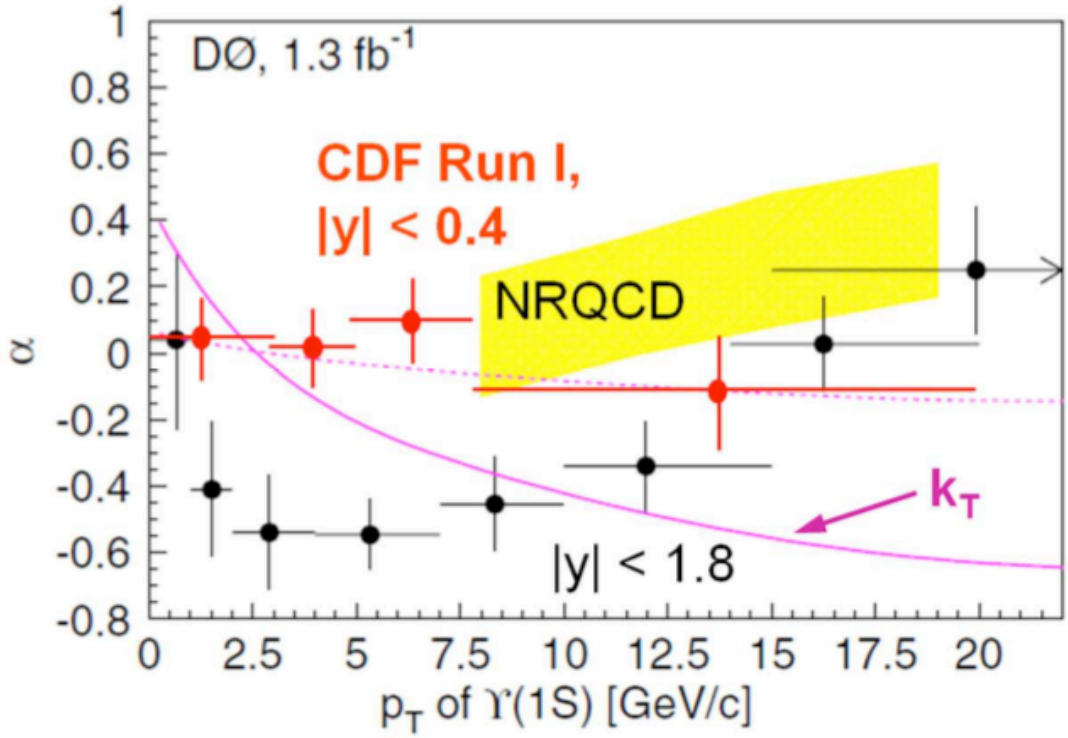
Transverse: $\frac{d\sigma}{d\cos\theta^*} \sim 1 + \cos^2\theta^*$

Longitudinal: $\frac{d\sigma}{d\cos\theta^*} \sim 1 - \cos^2\theta^*$

(this is called the s-channel helicity frame)

Muon selection: minimum p_t cut (muon must penetrate the muon detector, be triggered, and reconstruct as a muon) sculpts the θ* distribution

Recent Status



- CDF found no evidence for polarization in Run I

  Phys. Rev. Lett. 88, 161802 (2002).

- DØ finds it to be longitudinal at low p_T, then transverse at high p_T

  Phys. Rev. Lett. 101, 182004 (2008).

- Models:
  - NRQCD – Braaten & Lee, Phys. Rev. D63, 071501(R) (2001)
  - k_T – Baranov & Zotov, JETP Lett. 86, 435 (2007)
- Newer NLO calculations show similar trends:
  - NLO NRQCD – Gong, Wang & Zhang, Phys. Rev. D83, 114021 (2011)
  - Color singlet NNLO* - Artoisenent, *et al.* Phys. Rev. Lett. 101, 152001 (2008)

slide courtesy M. Jones

- The current situation is unsatisfactory... are we missing something obvious? Pietro Faccioli emphasizes basic quantum mechanics...
- Back to the fundamentals:

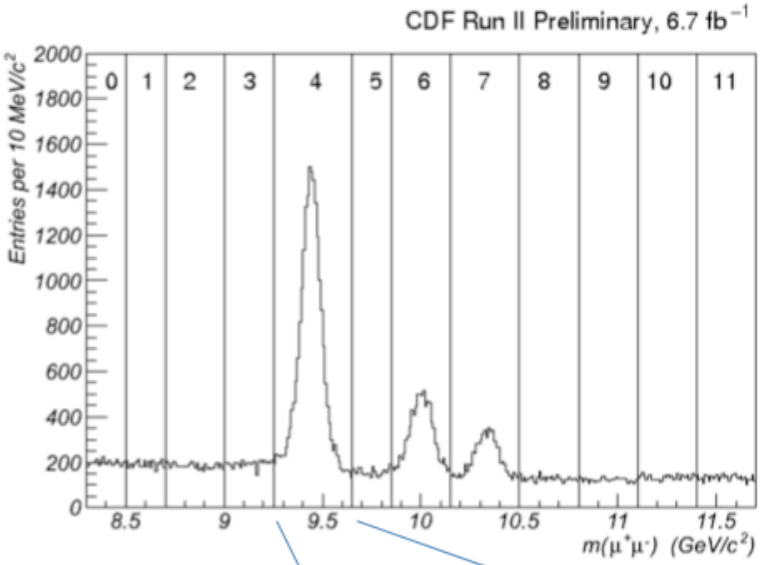
$$\frac{dN}{d\Omega} \propto 1+\lambda_\theta \cos^2\theta+\lambda_\phi \sin^2\theta \cos 2\phi+\lambda_{\theta\phi} \sin 2\theta \cos\phi$$

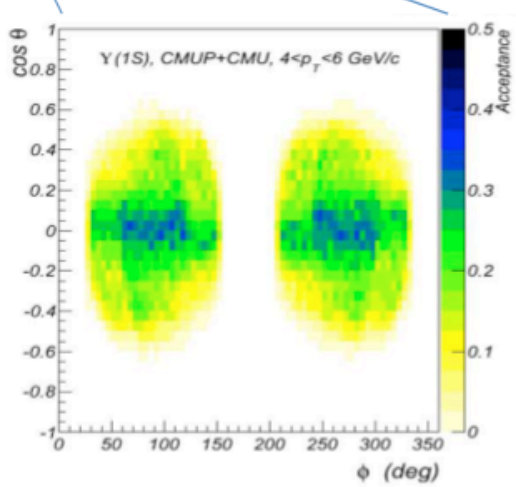
$$\lambda_\theta = \frac{\rho_{11}-\rho_{00}}{\rho_{11}+\rho_{00}} \quad \lambda_\varphi = \frac{\rho_{1,-1}}{\rho_{11}+\rho_{00}} \quad \lambda_{\theta\varphi} = \frac{\rho_{10}}{\rho_{11}+\rho_{00}}$$

- Un-polarized only when λ_θ, λ_φ and $\lambda_{\theta\varphi}$ are *all* zero.

Earlier measurements used only the s-channel helicity frame and thus could measure only λ_θ. New CDF measurement uses also the Collins-Soper frame which allows measurement of all three components

Analysis Method





Geometric and trigger acceptance calculated using Monte Carlo

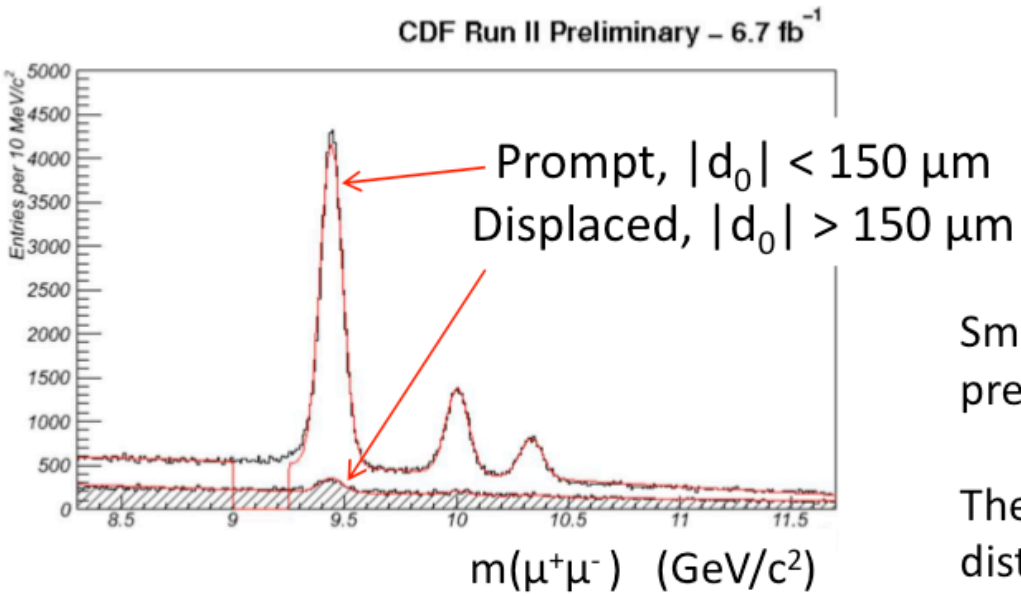
- Both signal and background are present
- Conceptual problem:

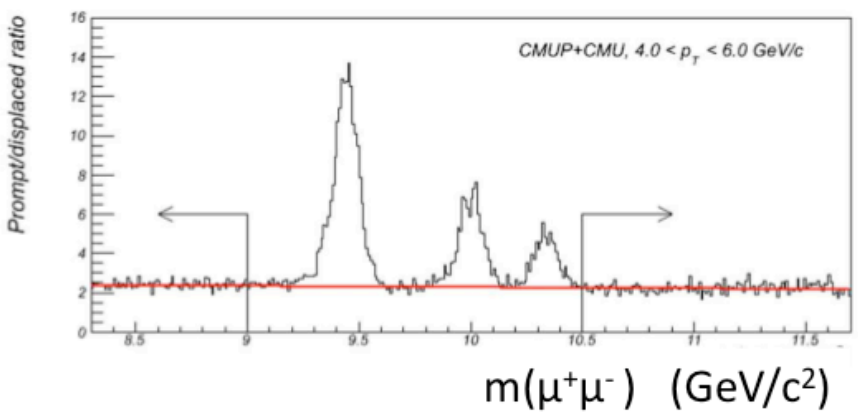
$$\bar{\lambda} = f_s \lambda_s + (1 - f_s)\lambda_b$$

- Signal fraction obtained from fit to mass distribution
- How to constrain angular distribution of the background?
- Side-band extrapolation?
  - Does it vary smoothly enough?
  - Probably not…

slide courtesy M. Jones

Background Proxy Sample





Small fraction of the ϒ signal is still present in the displaced sample (1-4%)

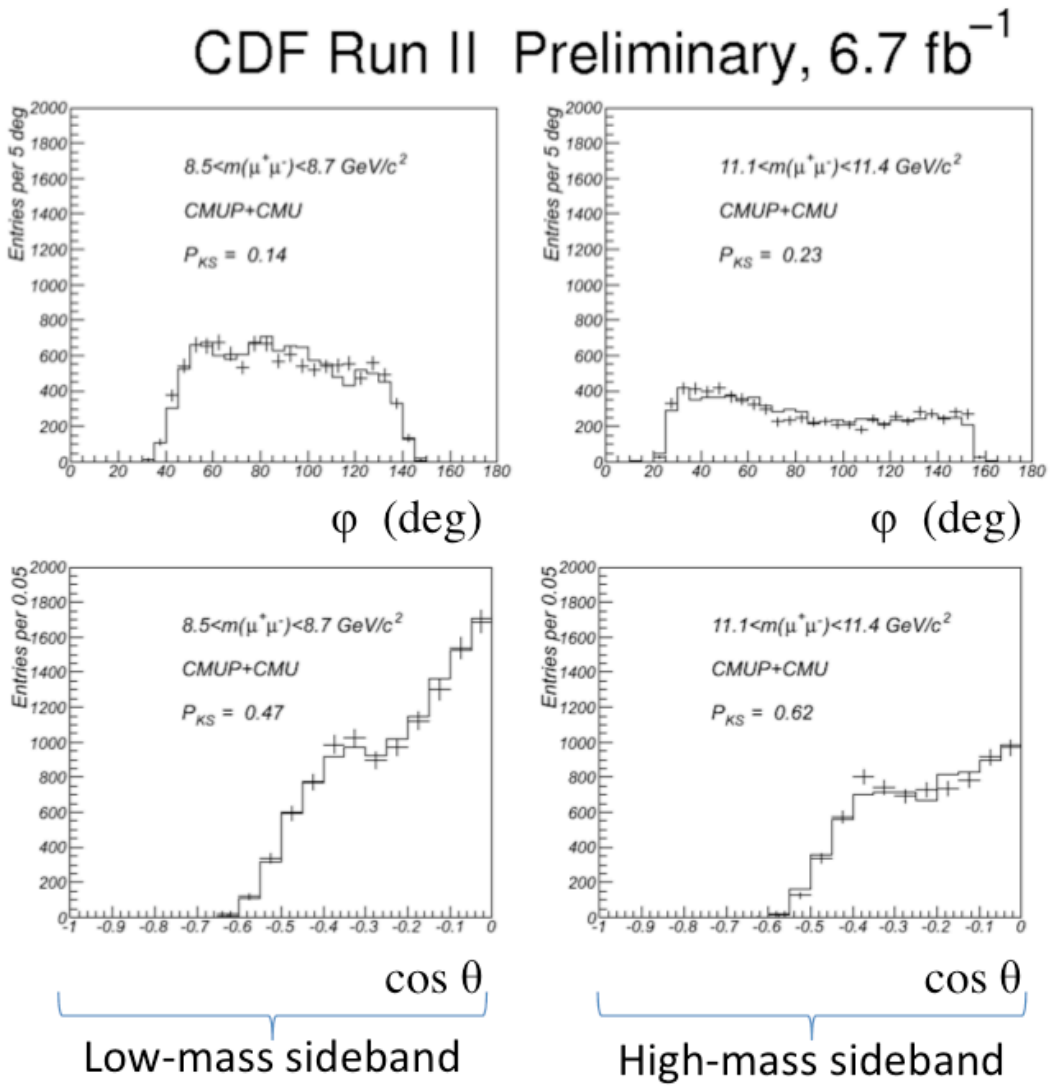
The ratio of prompt/secondary distributions is almost constant.

Simultaneous fit to displaced sample and ϒ sidebands avoids possible bias from modeling the ϒ line shape.

Quadratic scale factor function considered in systematic studies

slide courtesy M. Jones

Angular distributions in sidebands

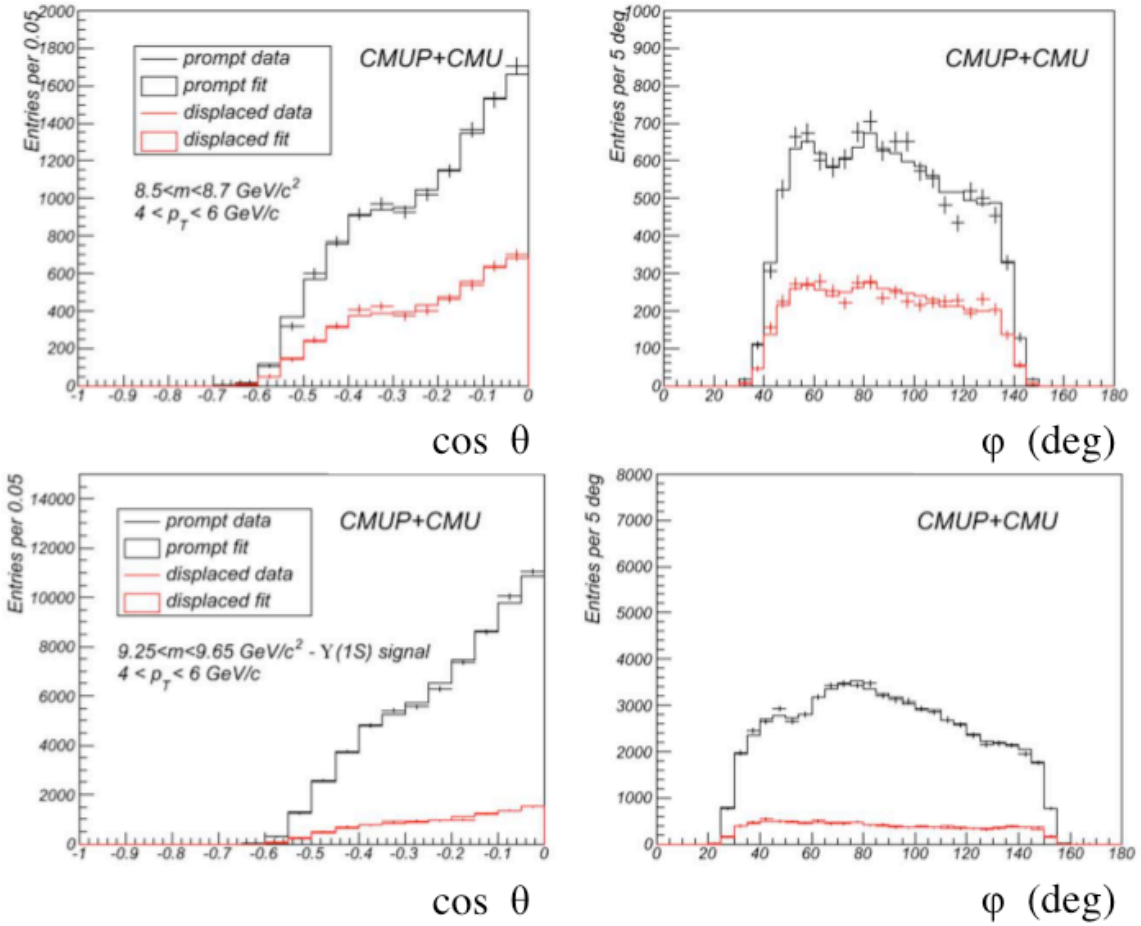


- The sub-sample containing a displaced track ($|d_0| > 150$ μm) is a good description of the background under the ϒ(nS):
- Prompt (histogram) and displaced (error bars) angular distributions match in the sidebands.
- We use the displaced muon sample to constrain the angular distribution of background under the ϒ(nS) peaks.

slide courtesy M. Jones

Fits to signal + background

CDF Run II Preliminary, 6.7 fb^{-1}



Only background

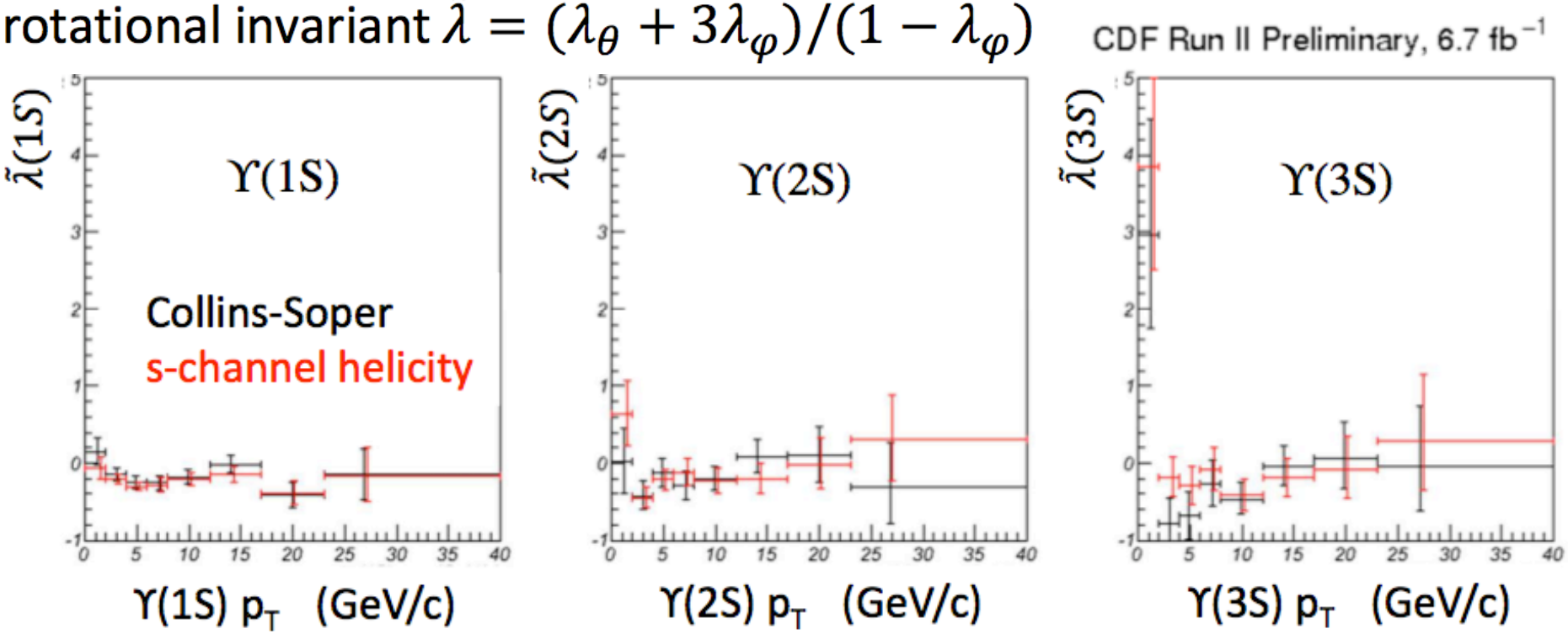
Υ(1S) signal + background

- The fit provides a good description of the angular distribution in both background and in signal + background mass bins.

 slide courtesy M. Jones

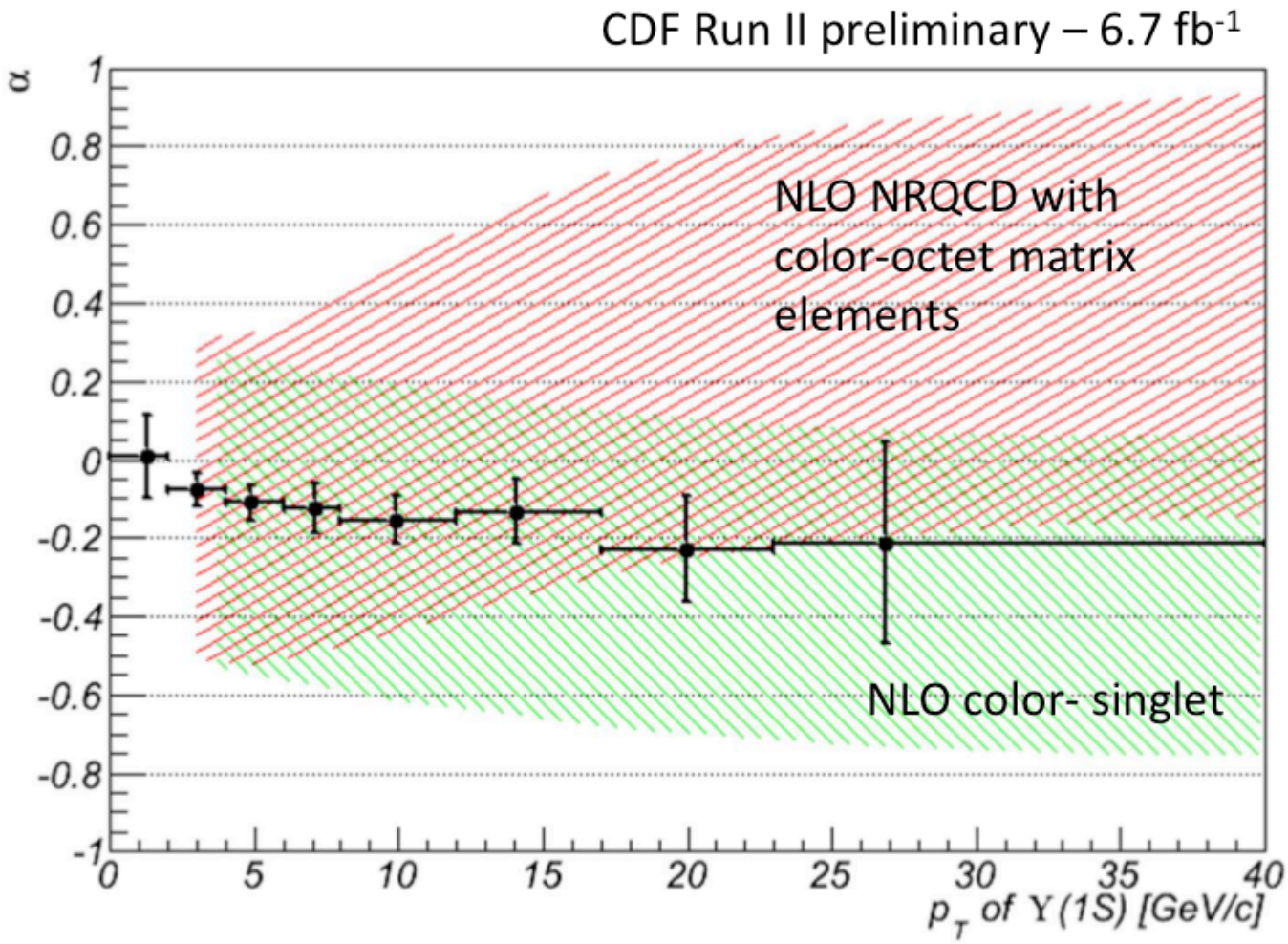
Frame Invariance Tests

rotational invariant $\tilde{\lambda} = (\lambda_\theta + 3\lambda_\varphi)/(1 - \lambda_\varphi)$



- Differences generally consistent with size of statistical fluctuations seen in toy Monte Carlo experiments
- Differences used to quantify systematic uncertainties on λ_θ, λ_φ and $\lambda_{\theta\varphi}$

Comparisons with newer calculations



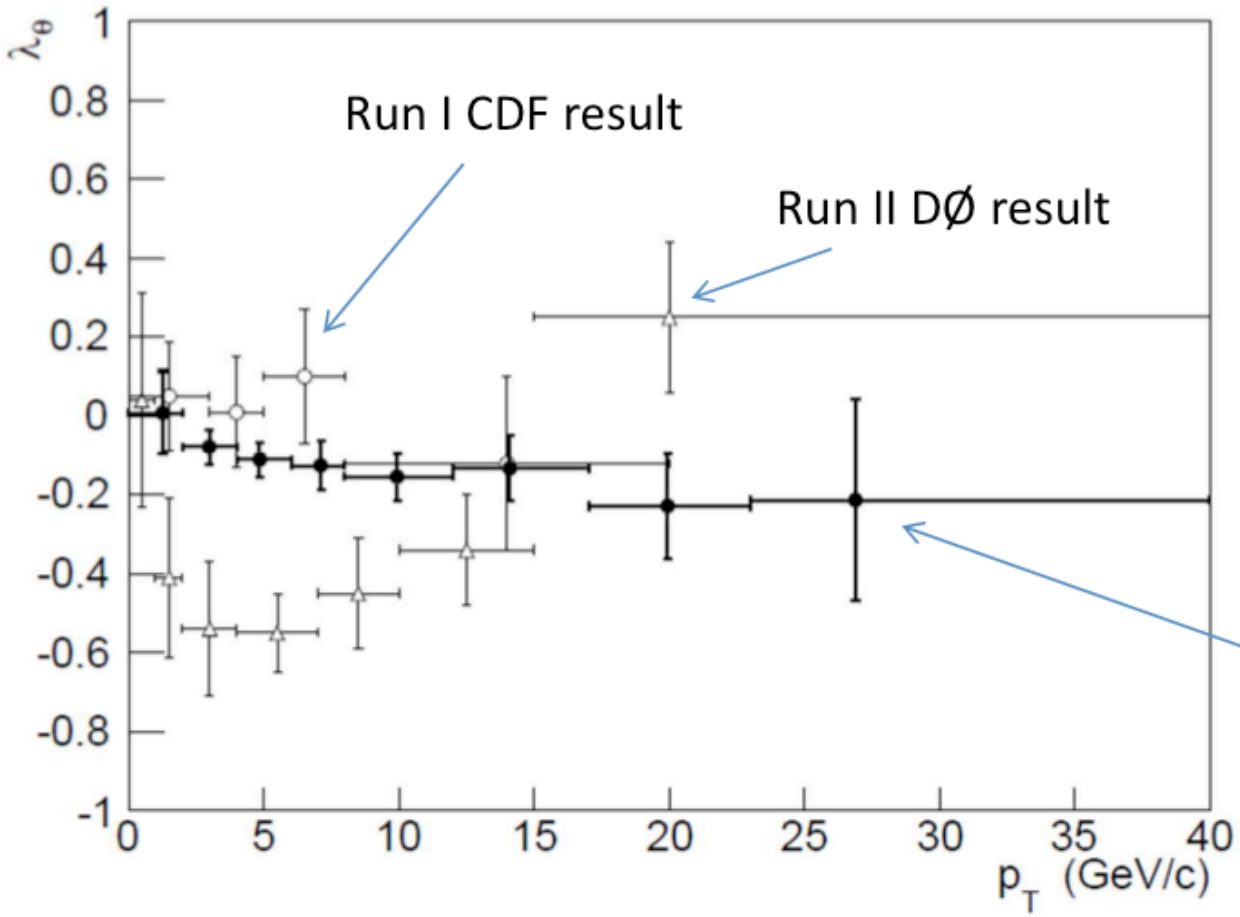
Significant uncertainty due to feed-down from $\chi_b(nP)$ states (conservative assumptions)

slide courtesy M. Jones

Nucl. Phys. B 214, 3 (2011) summary:

- NLO NRQCD – Gong, Wang & Zhang, Phys. Rev. D83, 114021 (2011)
- Color-singlet NLO and NNLO* - Artoisenent, *et al.* Phys. Rev. Lett. 101, 152001 (2008)

Comparison with Previous Measurements



s-channel helicity frame measurements

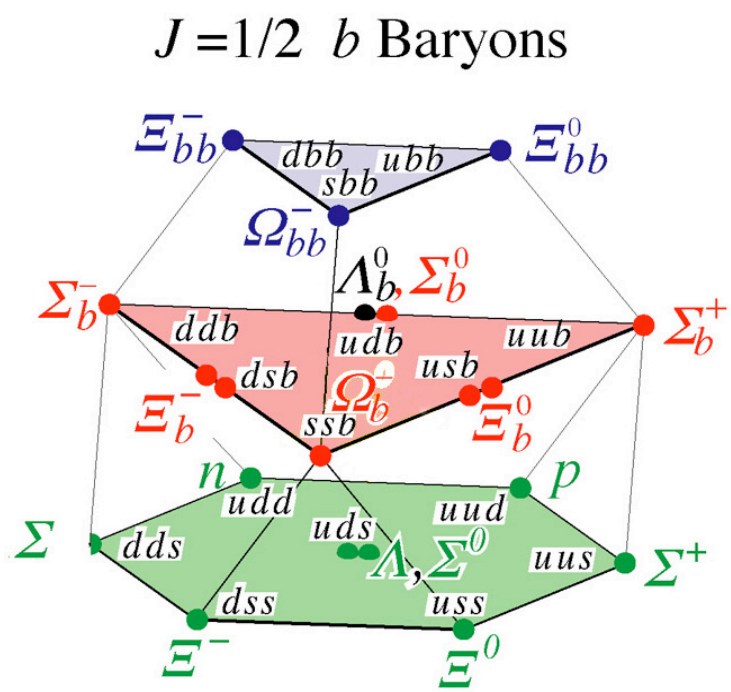
New ϒ(1S) result

slide courtesy M. Jones

B Baryon Ground States

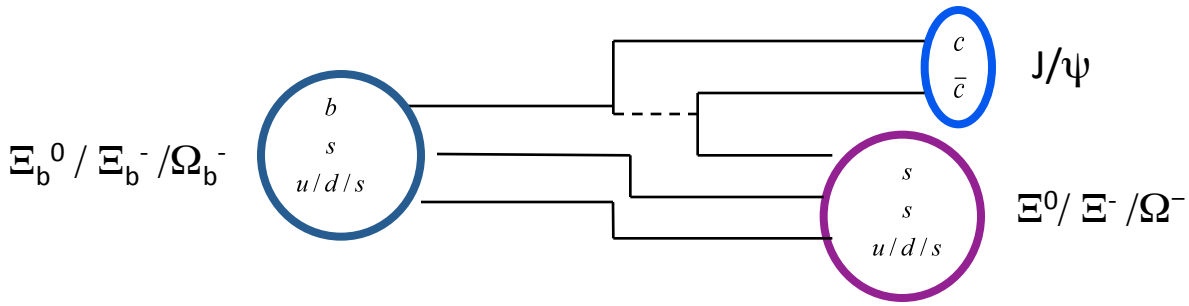
- A reminder of the status of ground state *b* baryons
  - Λ_b, observed in 1990's
  - $\Sigma_b^{\pm}$, observed in 2007
  - Ξ_b^-, observed in 2007
  - Ω_b^-, observed in 2008,2009
    - The Ω_b^- results disagree

- Ξ_b^0, observed 2011 (CDF) this result



P. Lukens

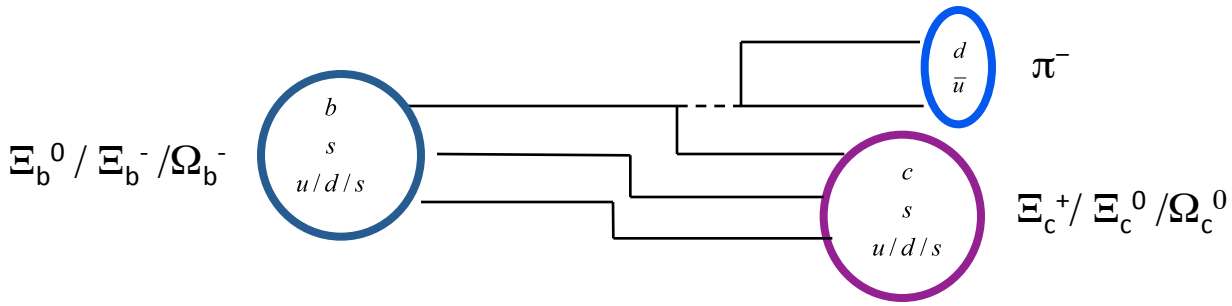
Strange, *b* Baryons with a J/ψ Final State



- So far, the Ξ_b^- and Ω_b^- have been seen through the processes
  - $\Xi_b^- \to J/\psi\ \Xi^-$, $J/\psi \to \mu^+\mu^-$, $\Xi^- \to \Lambda\pi^-$
  - $\Omega_b^- \to J/\psi\ \Omega^-$, $J/\psi \to \mu^+\mu^-$, $\Omega^- \to \Lambda K^-$
- The analogue for the Ξ_b^0 is inaccessible for CDF
  - $\Xi_b^0 \to J/\psi\ \Xi^0$, $J/\psi \to \mu^+\mu^-$, $\Xi^0 \to \Lambda\pi^0$

P. Lukens

Alternative Channels



- Alternative final states with a π^- could be expected
  - $\Xi_b^0 \to \Xi_c^+\pi^-$, $\Xi_c^+ \to \Xi^-\pi^+\pi^+$
  - $\Xi_b^- \to \Xi_c^0\pi^-$, $\Xi_c^0 \to \Xi^-\pi^+$
  - $\Omega_b^- \to \Omega_c^0\pi^-$, $\Omega_c^0 \to \Omega^-\pi^+$
- The analogue $\Lambda_b \to \Lambda_c^+\pi^-$ has been known for some time.
- These lack muons, so they must be found through another trigger mechanism. CDF's two-track trigger is used.

P. Lukens

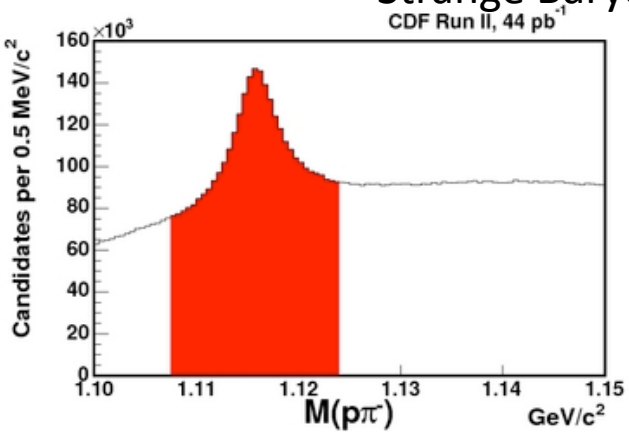
Chasing the Ξ_b^0 Decay Chain

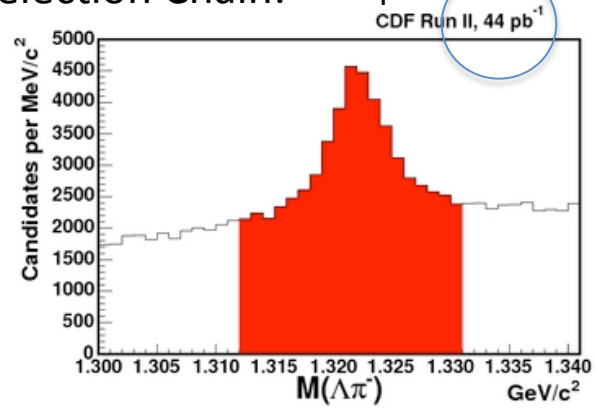
$$\Xi_b^0 \rightarrow \Xi_c^+ \pi^-,\ \Xi_c^+ \rightarrow \Xi^- \pi^+ \pi^+,\ \Xi^- \rightarrow \Lambda \pi^-,\ \Lambda \rightarrow p \pi^-$$

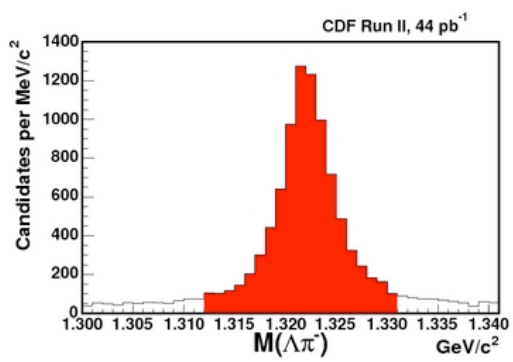
Does not use J/Ψ in the decay chain!

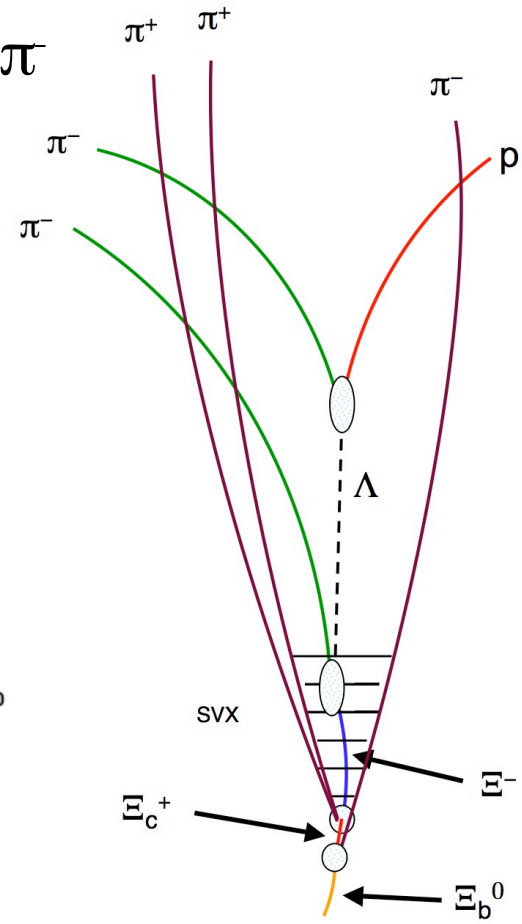
Strange Baryon Selection Chain:

Small Data Sample









Requiring silicon hits on the Ξ^- track, and impact parameter less than 100 μm

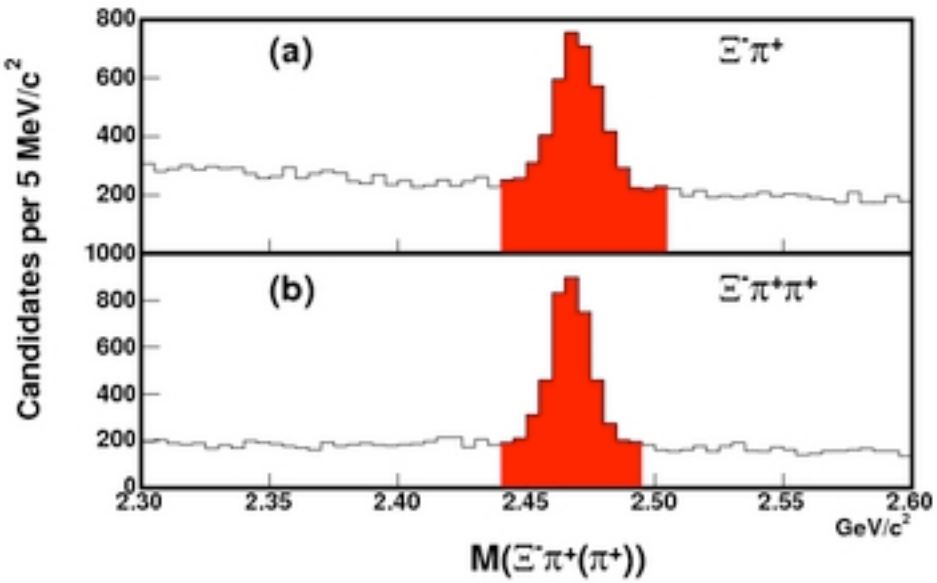
arXiv:1107.4015

Reconstruction of the Ξ_c^0 and Ξ_c^-

The neutral Cascade-c provides a route to observe the charged Cascade-b

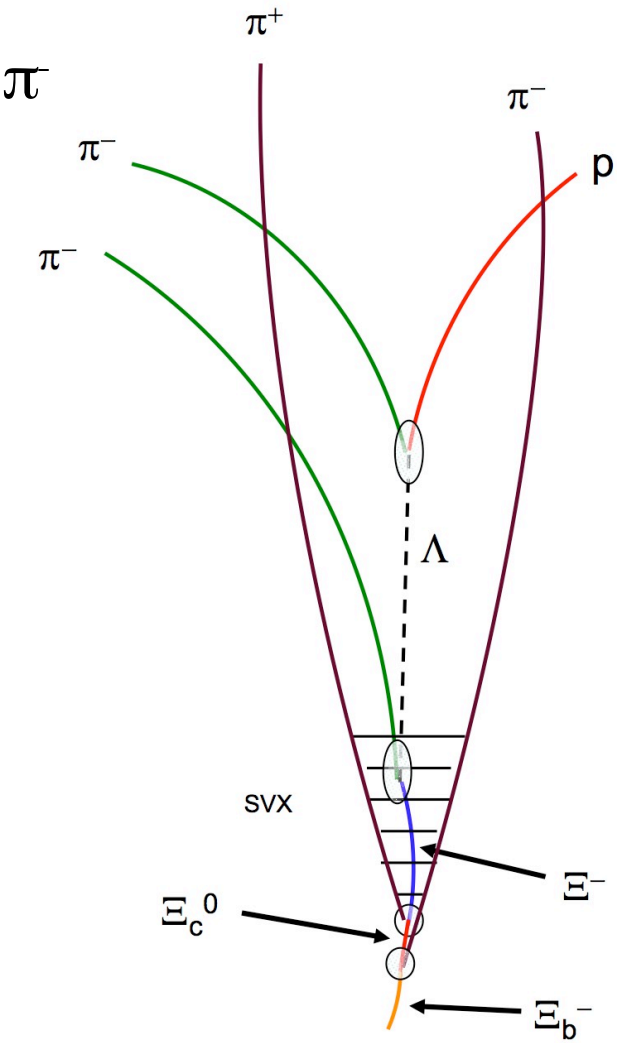
$$\Xi_b^- \rightarrow \Xi_c^0\, \pi^-,\ \Xi_c^0 \rightarrow \Xi^-\, \pi^+,\ \Xi^- \rightarrow \Lambda\, \pi^-,\ \Lambda \rightarrow p\, \pi^-$$

The difference is the lack of the second charged pion in the Ξ_c^0 decay compared with Ξ_c^+



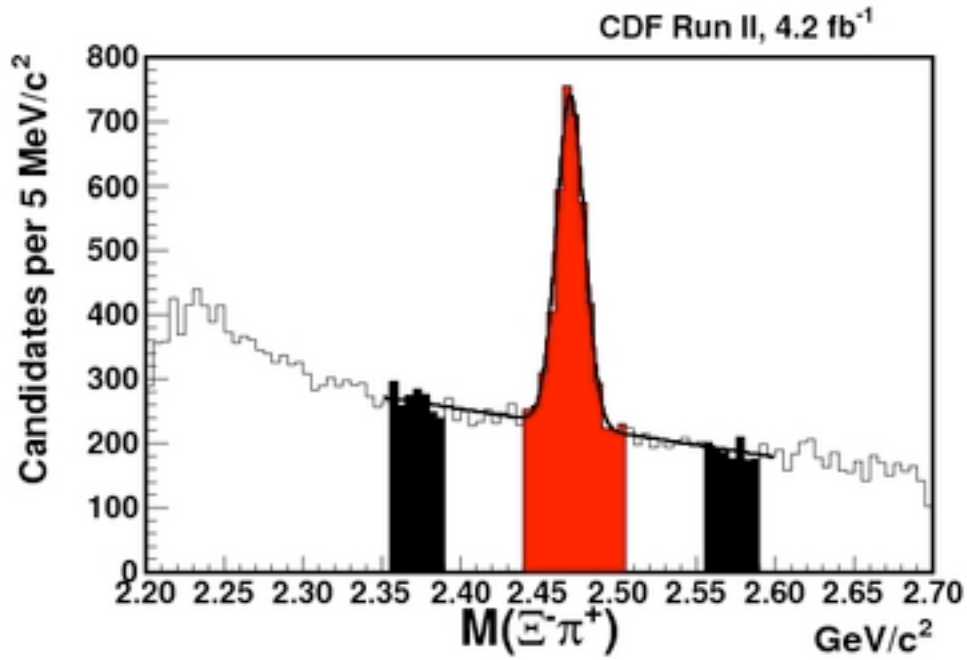
Ξ_c^0

Ξ_c^+



Charmed baryons

- A nice Ξ_c^0 signal can be found in the $\Xi^-\pi^+$ final state
  - $ct > 100\ \mu m$
- A simple Gaussian fit was imposed on the mass distribution
  - Resolution of 9 MeV/c^2

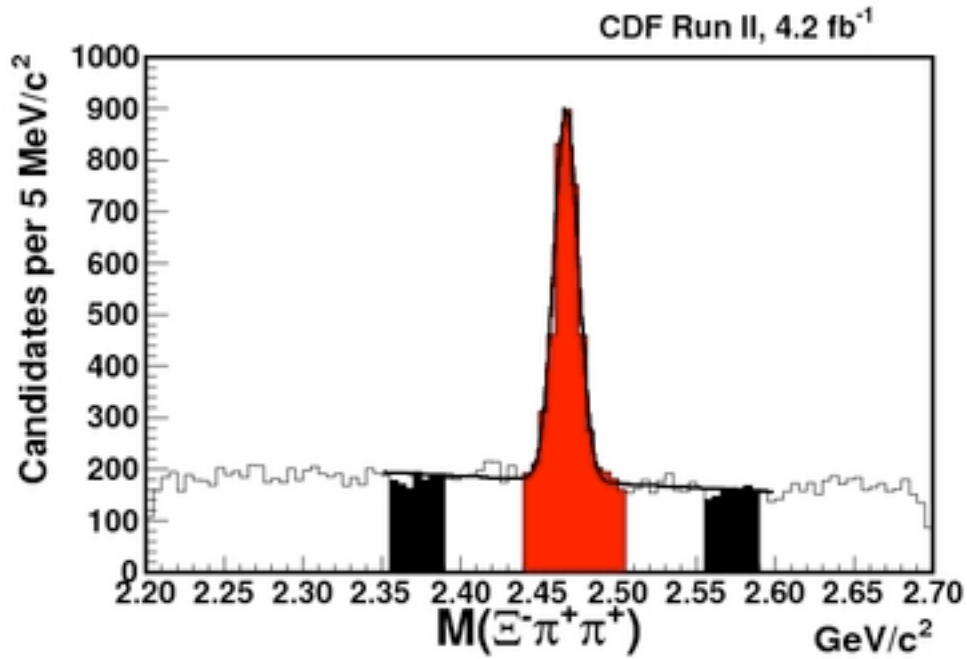


- Red is the signal range
  - Black are sidebands used to
  - constrain background

P. Lukens

Charmed baryons

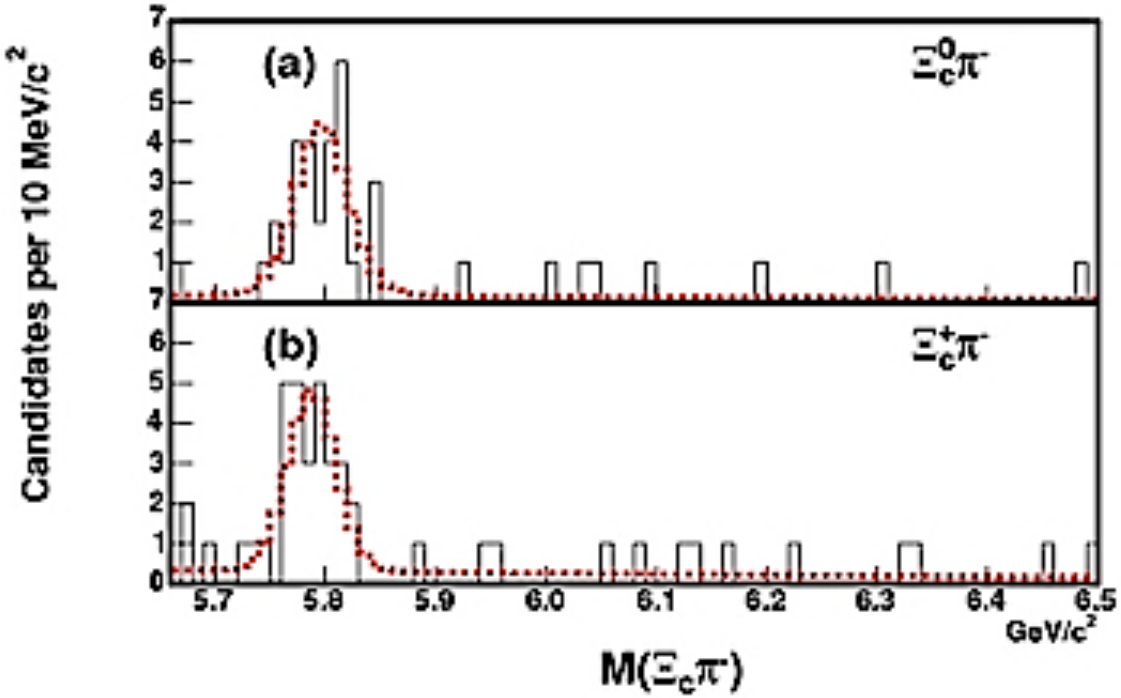
- A nice Ξ_c^+ signal can be found in the $\Xi^-\pi^+\pi^+$ final state
  - $ct > 100\ \mu m$
- A simple Gaussian fit was imposed on the mass distribution
  - Resolution of 8 MeV/c^2



- Red is the signal range
  - Black are sidebands used to constrian
  - backgrounds

P. Lukens

Spectroscopy of the Ξ_b^- and Ξ_b^0 Baryons



This is the first observation of the Ξ_b^- in this final state.
And the first observation of Ξ_b^0 in any final state

	Mass (MeV/c2)
Ξ^-_b	5796.7 ± 5.1 ± 1.4
Ξ^0_b	5787.8 ± 5.0 ± 1.3

$$M(\Xi_b^-) - M(\Xi_b^0) = 3.1 \pm 5.6(stat.) \pm 1.3(syst.)$$

The Low-Energy Run

ENERGIES

Log s (= spacing appropriate)

Tevatron Run 2

Results in preparation

Other pp(bar) energies

√s (GeV)

1960 (Standard)

1800 (Run 1)

900 (~~SppS~~, LHC(pp))

630 (SppS, TeV I)

540 (SppS, TeV I)

300 (Injection; max lever arm)

200 (RHIC(pp) ~~SppS~~)

ISR (max 63 GeV)

~~SppS~~ was a ramping run, UA5 streamer chamber. 4K & 7K Min Bias events only.