First observation of $\overline{B}_s^0 \to D_s^{\pm} K^{\mp}$

Towards measuring γ in the B_s sector

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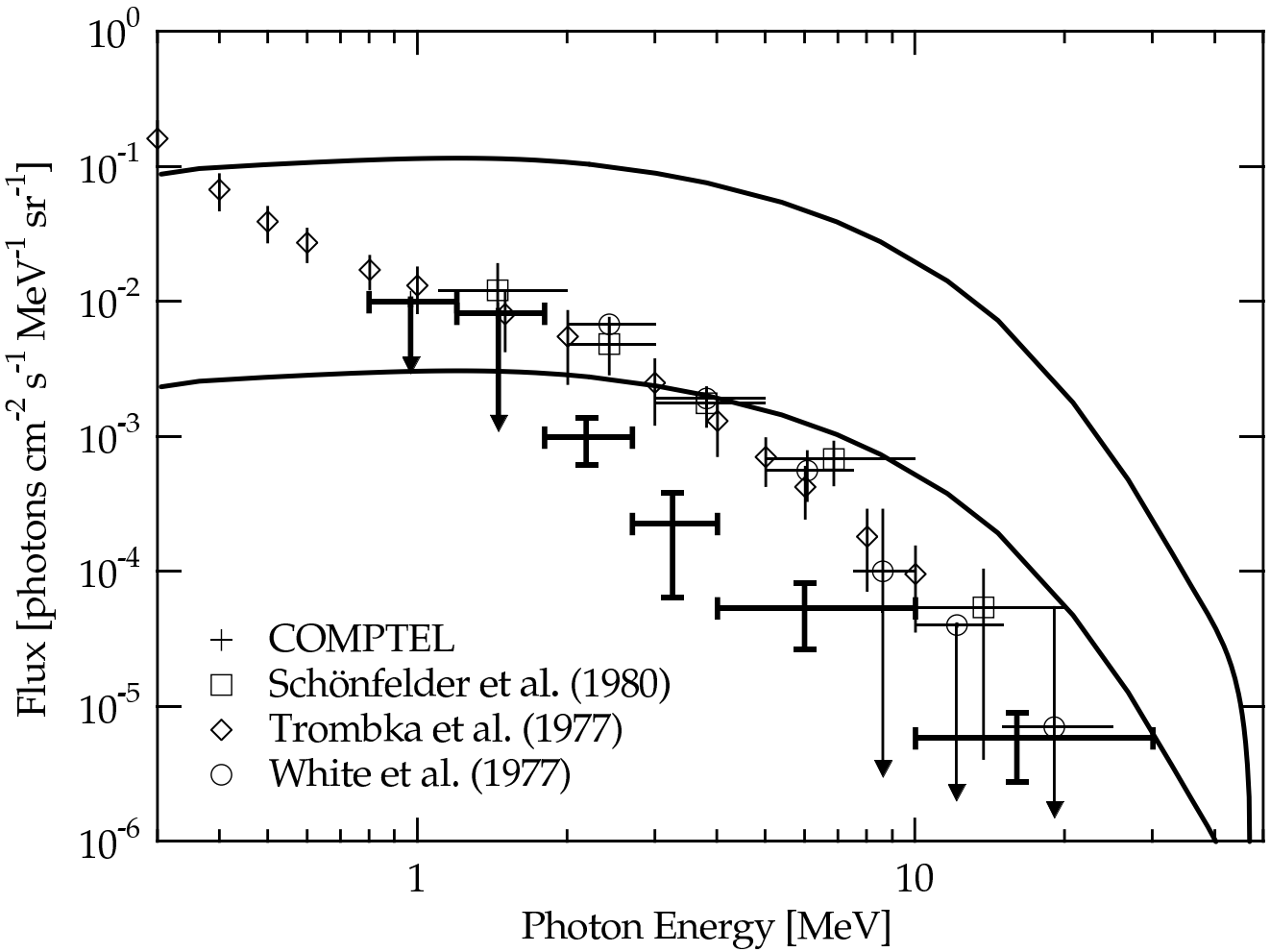
Outline

- Physical motivation
  - γ is the least-known CKM angle
  - $\overline{B}_s^0 \to D_s^\pm K^\mp$ is a place to measure γ
  - disentangling $\overline{B}_s^0 \to D_s^\pm K^\mp$ from $\overline{B}_s^0 \to D_s^+ \pi^-$ is the first step
  - $\mathcal{B}(\overline{B}_s^0 \to D_s^\pm K^\mp)/\mathcal{B}(\overline{B}_s^0 \to D_s^+ \pi^-)$ not previously measured
  - potentially very different from $\overline{B}^0 \to D^+ K^-$
- The experiment
  - Tevatron
  - CDF
- Analysis strategy
  - event selection
  - unbinned maximum-likelihood fit to separate $\overline{B}_s^0 \to D_s^\pm K^\mp$
  - control samples
  - fit projections
  - systematic uncertainties
- Result: $\mathcal{B}(\overline{B}_s^0 \to D_s^\pm K^\mp)/\mathcal{B}(\overline{B}_s^0 \to D_s^+ \pi^-)$
- Prospects for γ

Standard model

- Describes everything seen at colliders
- But does not describe other phenomena, like baryogenesis
- So try to find discrepancy between data and SM in collider setting
- In particular, in the last 10 years (the B factory era), the standard-model description of CP violation has been put to the test



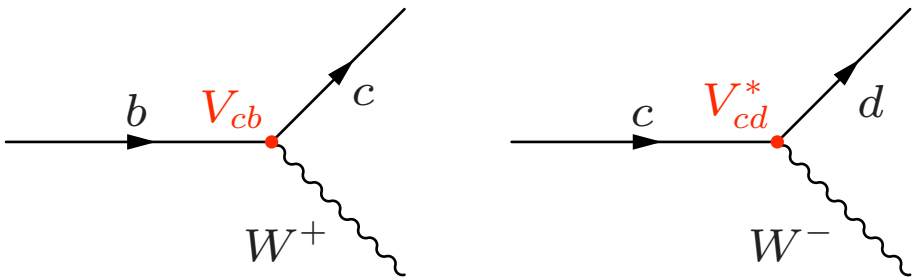
⇑ No large regions of antimatter in the universe[1]

[1] A. G. Cohen, A. De Rujula and S. L. Glashow, Astrophys. J. **495**, 539 (1998) [arXiv:astro-ph/9707087].

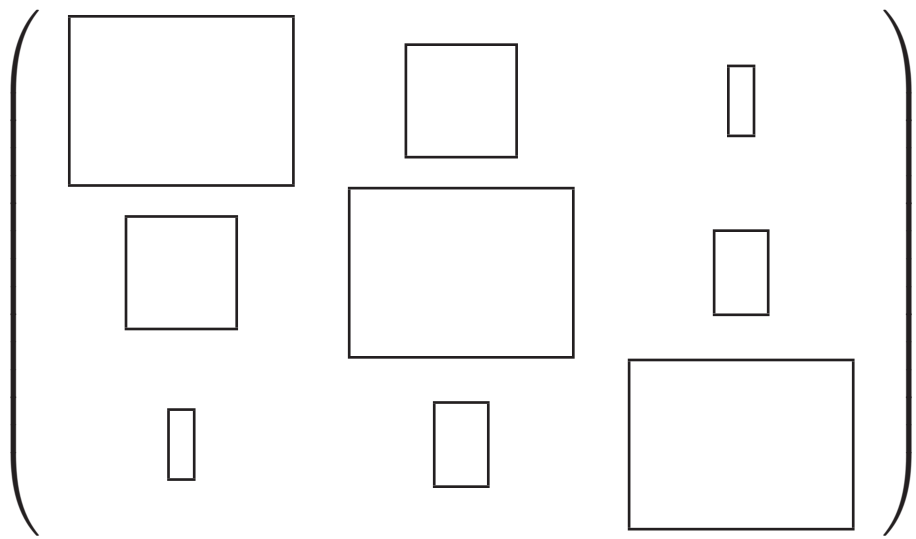
CKM matrix (1)

Where does Standard-model CP violation come from?

Weak quark eigenstates are not mass eigenstates:



$$V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} =$$

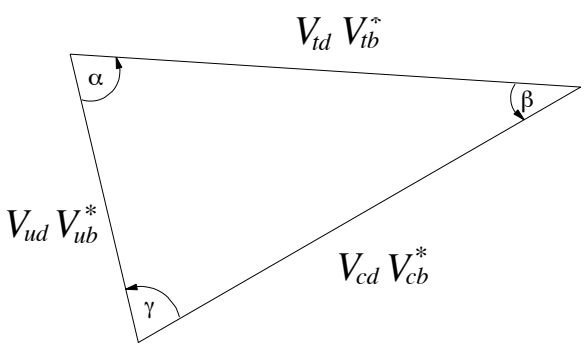


CKM matrix (2)

Hierarchy $\Rightarrow$ expansion in $\lambda = \sin\theta_C \approx 0.2$

$$V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$

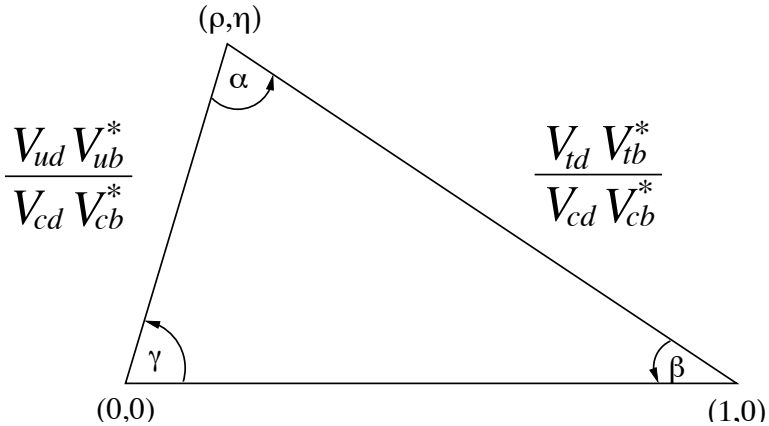
Complex CKM elements $\Rightarrow$ CP violation

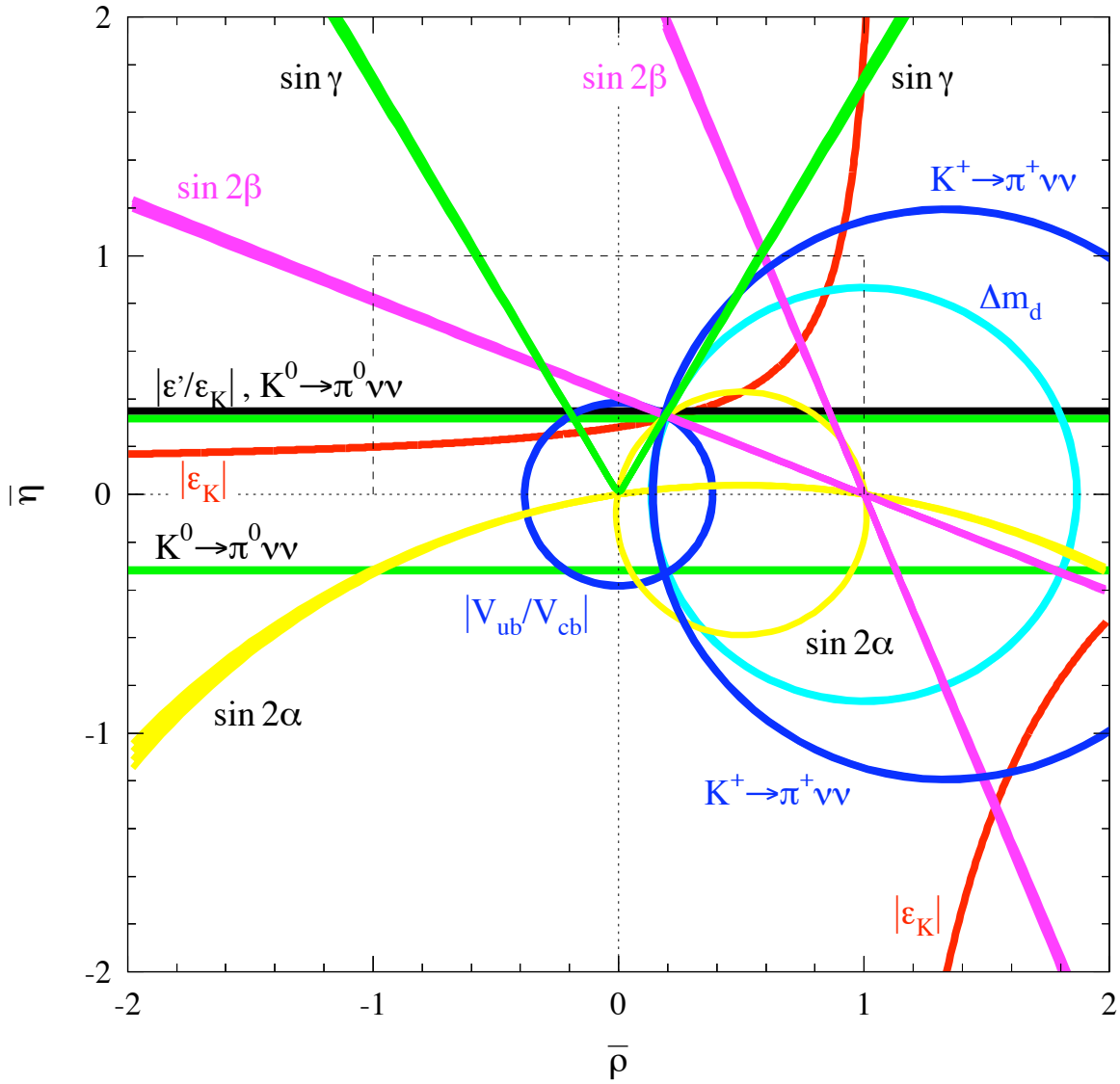


Unitarity: $V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$

CKM unitarity and new physics

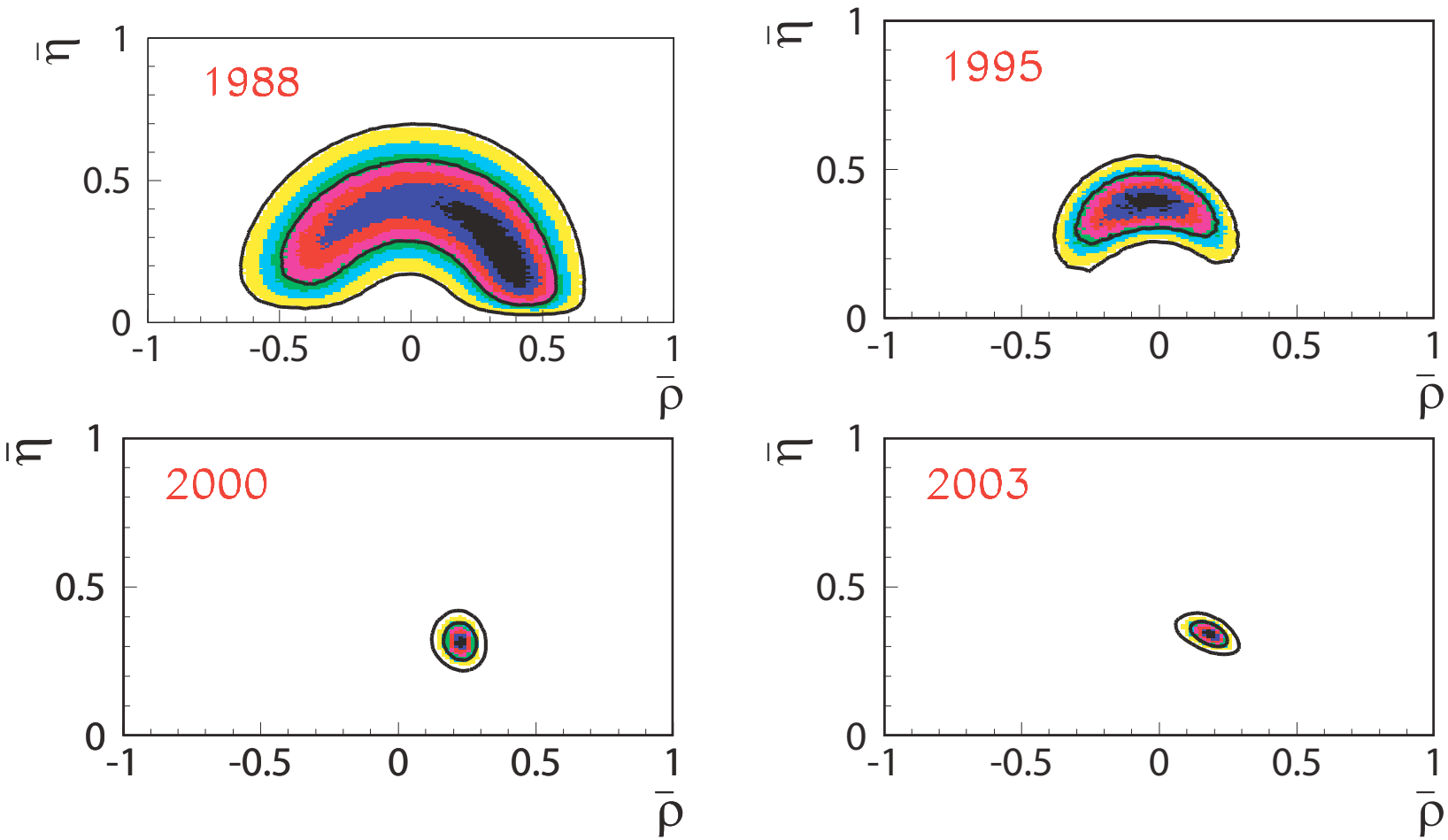
Experimental approach: overconstrain the unitarity triangle by measuring angles and sides



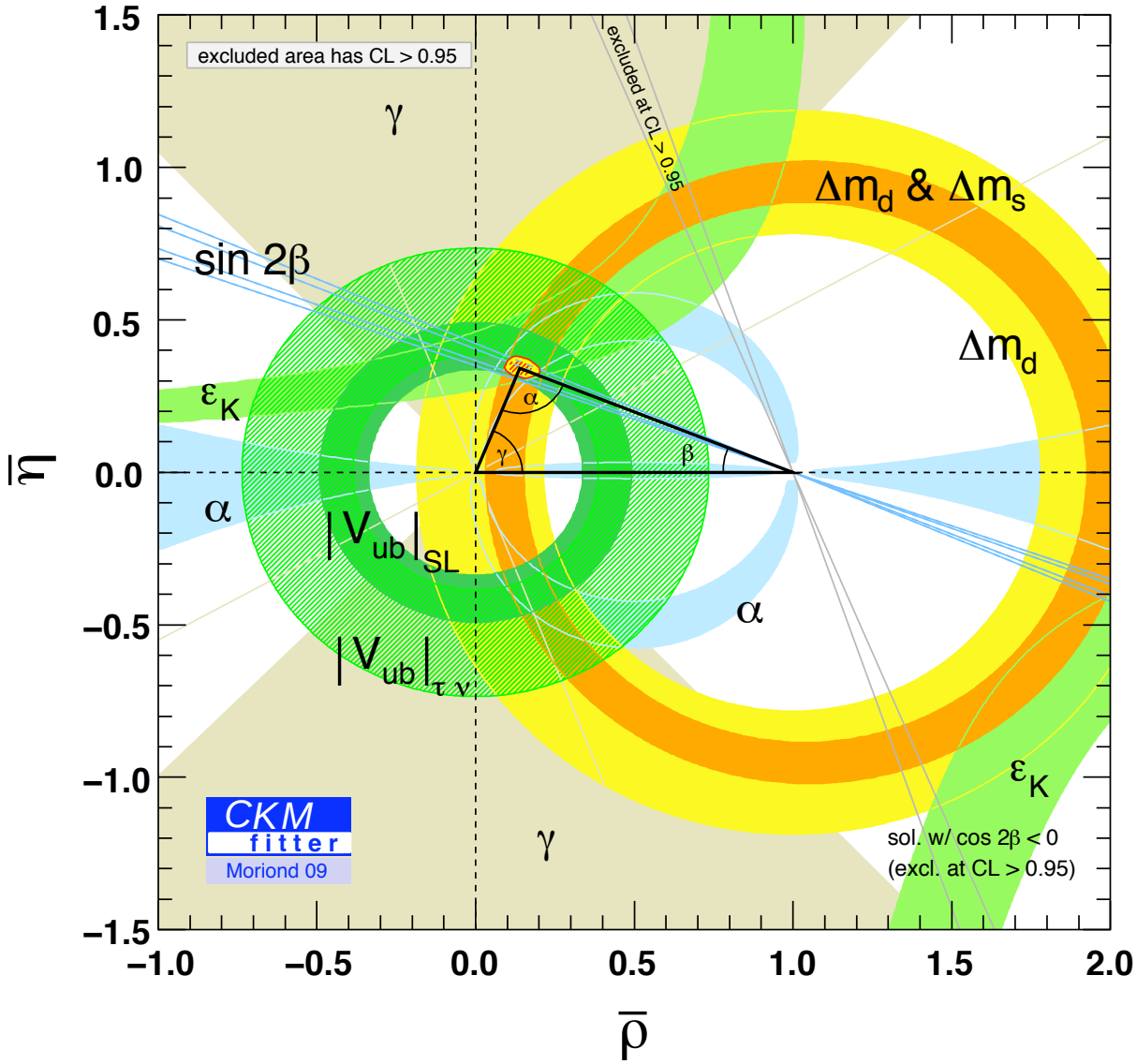


Unitarity triangle (1)

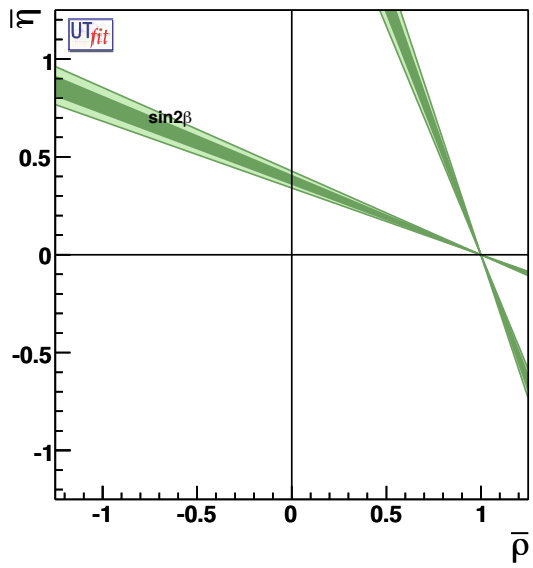
Our knowledge of the unitarity triangle has become a precision science in the last 20 years



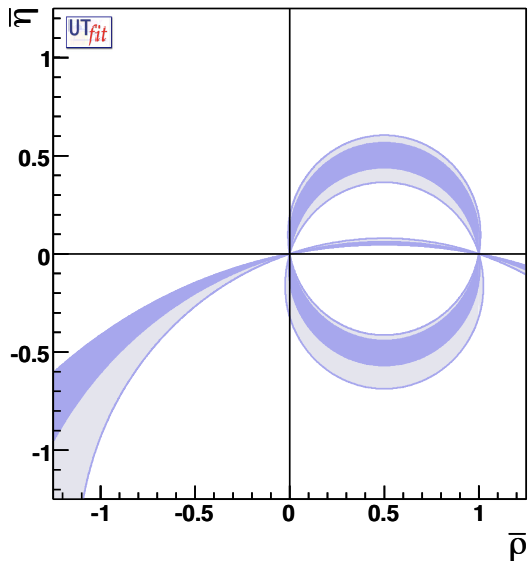
Unitarity triangle (2)



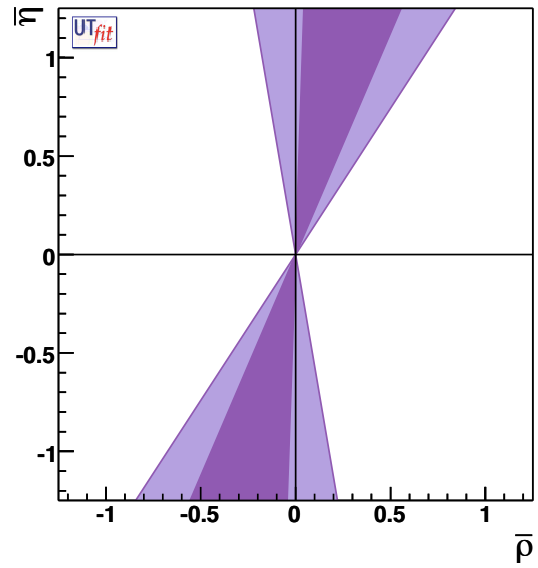
Unitarity triangle (3) — state of the angles



β



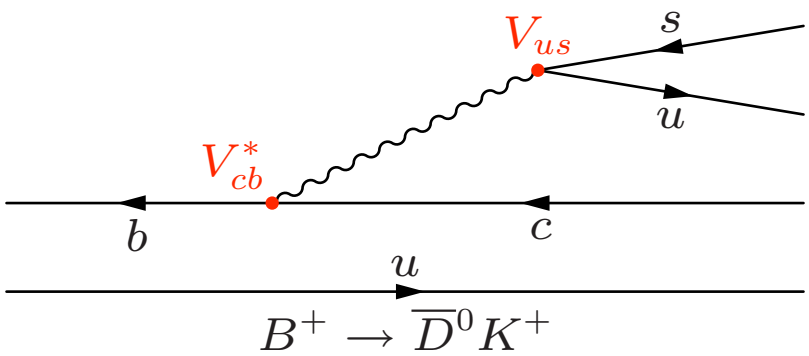
α

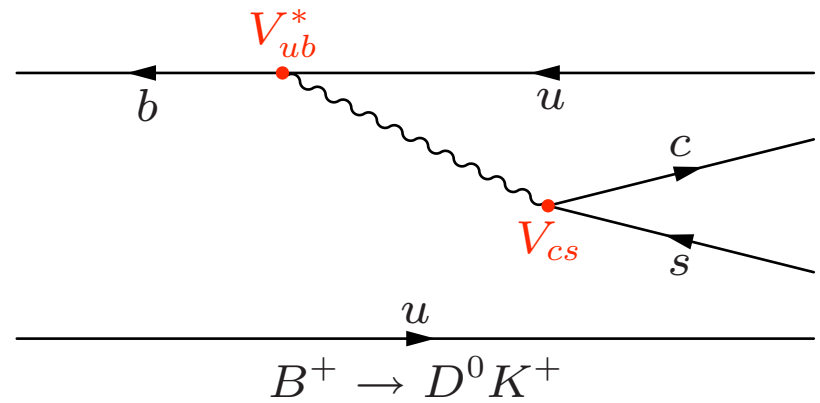


γ

γ

γ comes from interference of $b \to c$ and $b \to u$





Weak phase between diagrams is $\arg(-V_{ud}V_{ub}^*/V_{cd}V_{cb}^*) = \gamma$

But how to get interference?

Multiple methods:

GLW uses $D_{CP\pm} = \frac{1}{\sqrt{2}}(D^0 \pm \overline{D}^0)$; D^0, $\overline{D}^0$ decay to common $D_{CP+} \to K^+K^-$, $D_{CP+} \to \pi^+\pi^-$ final states[2]

ADS uses $D^0 \to K^-\pi^+$ and $\overline{D}^0 \to K^-\pi^+$ (doubly Cabibbo-suppressed)[3]

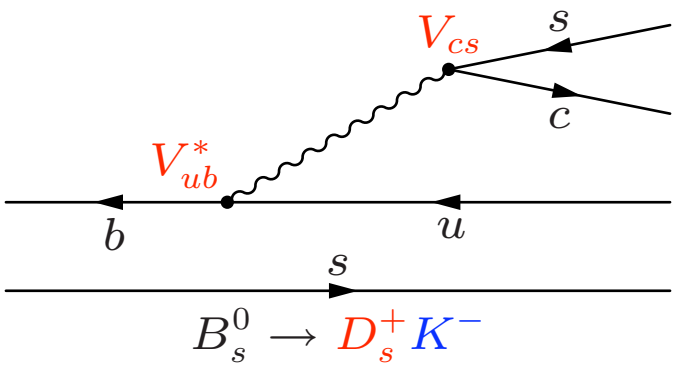
Dalitz plot multi-body D^0, $\overline{D}^0$ decays to common final states; advantage: no Cabibbo-suppressed D decays, large strong phases through resonances[4]

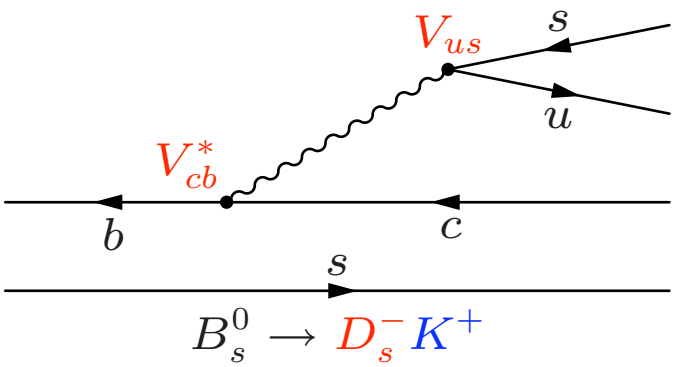
[2] M. Gronau and D. London., Phys. Lett. B **253**, 483 (1991); M. Gronau and D. Wyler, Phys. Lett. B **265**, 172 (1991); M. Gronau, Phys. Rev. D **58**, 037301 (1998) [arXiv:hep-ph/9802315].

[3] D. Atwood, I. Dunietz and A. Soni, Phys. Rev. D **63**, 036005 (2001) [arXiv:hep-ph/0008090].

[4] A. Giri, Y. Grossman, A. Soffer and J. Zupan, Phys. Rev. D **68**, 054018 (2003) [arXiv:hep-ph/0303187].

γ from $\overline{B}^0_s \to D^\pm_s K^\mp$



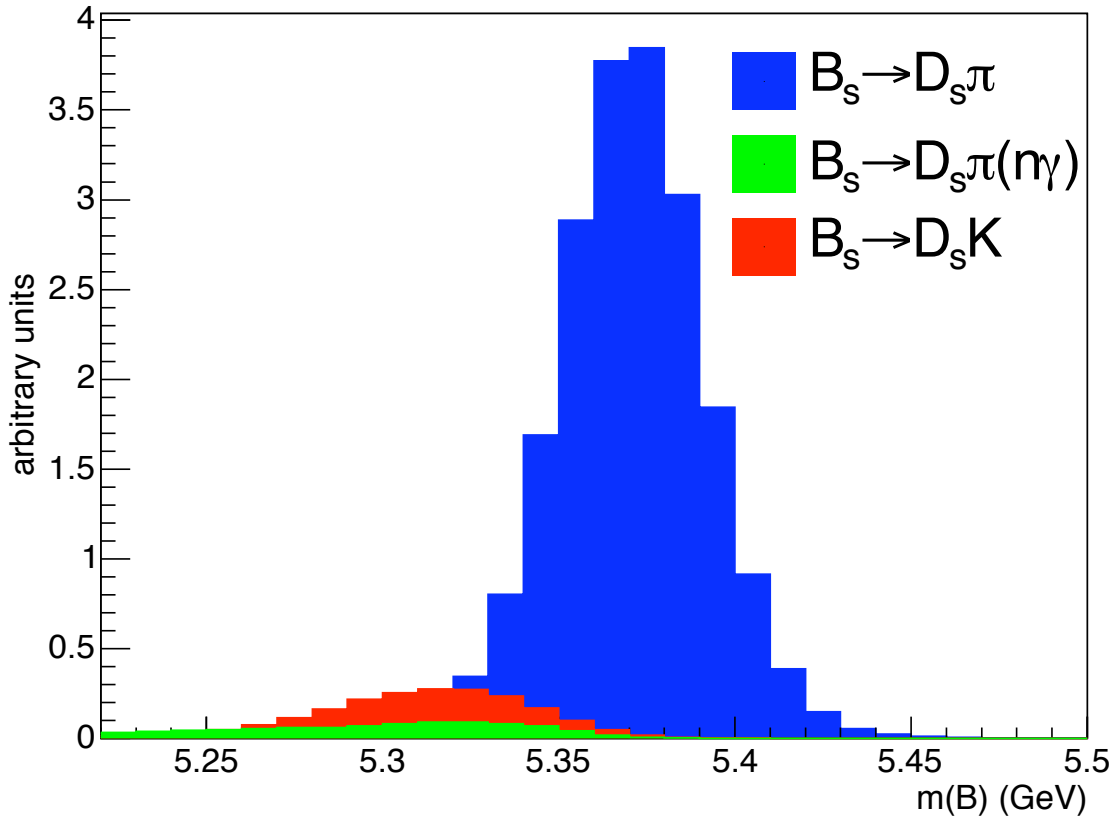


1. interference through mixing[5]
   - $B^0_s \to D^-_s K^+$ interferes with $B^0_s \xrightarrow{\text{(mixing)}} \overline{B}^0_s \to D^-_s K^+$
   - requires flavor tagging
   - frequency is very large
2. CP eigenstates[6]
   - interference because $B_{H,L} = pB + q\overline{B}$
   - no tagging
   - slow time evolution
   - but requires nonzero $\Delta\Gamma$

[5] R. Aleksan, I. Dunietz and B. Kayser, Z. Phys. C **54**, 653 (1992).
[6] I. Dunietz, Phys. Rev. D **52**, 3048 (1995) [arXiv:hep-ph/9501287].

First step in $\overline{B}_s^0 \to D_s^{\pm} K^{\mp}$: can we see the signal?

- Cabibbo-suppressed B decays are hard!



- If we can see the signal, we can measure $\mathcal{B}(\overline{B}_s^0 \to D_s^{\pm} K^{\mp}) / \mathcal{B}(\overline{B}_s^0 \to D_s^{+} \pi^{-})$
- Result could be very different from B^0 case

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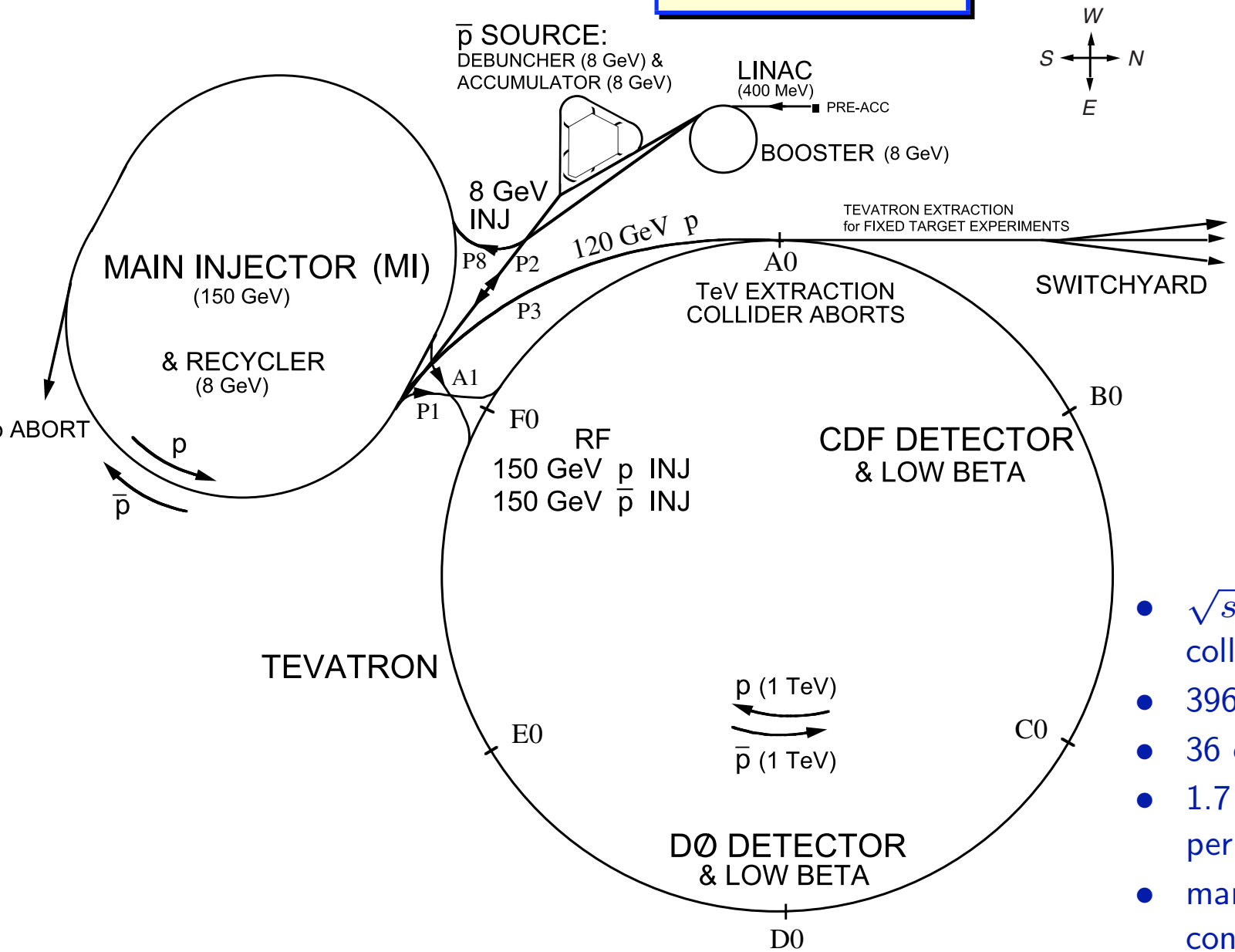
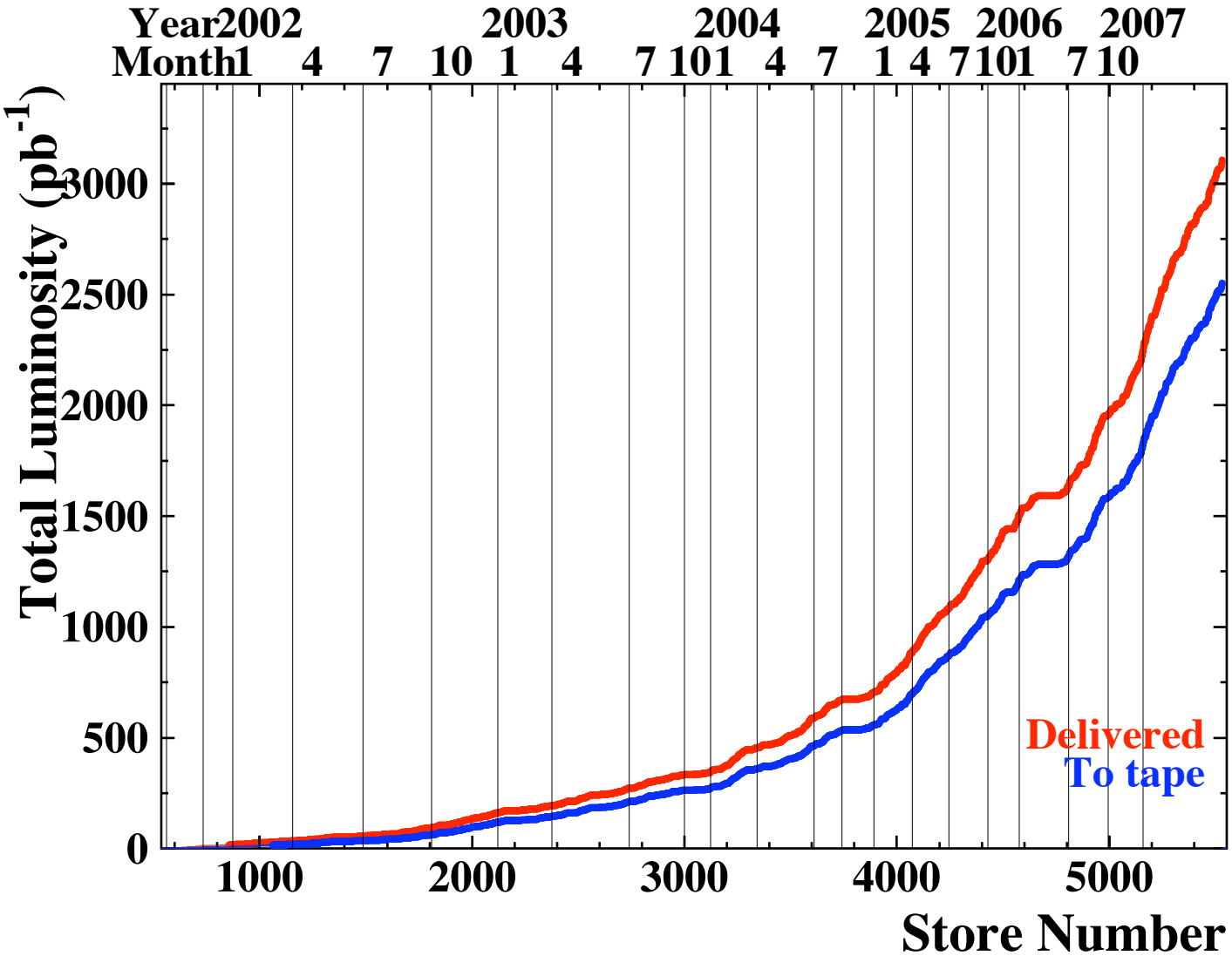
Tevatron



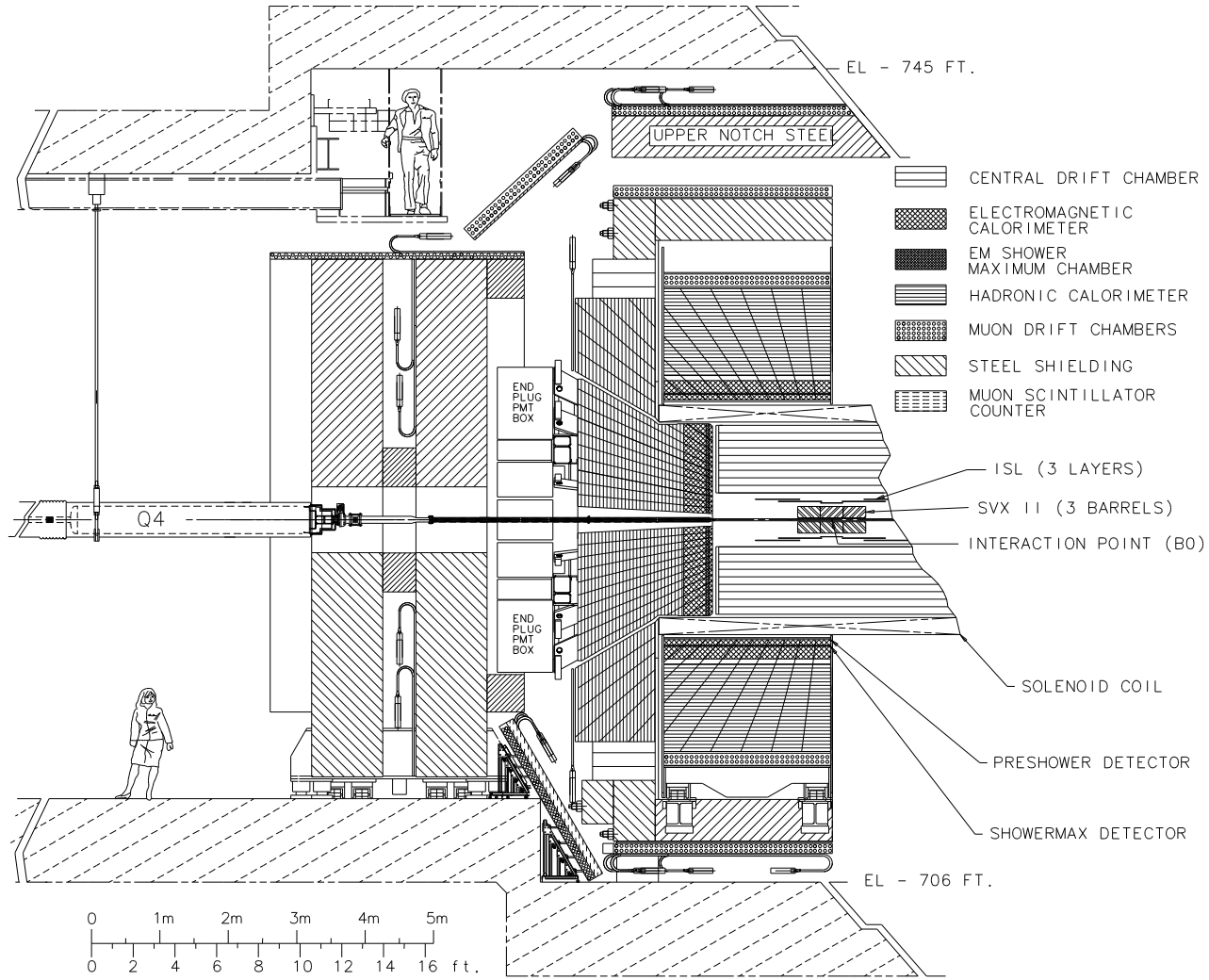
- $\sqrt{s} = 1.96$ TeV $p\overline{p}$ collisions
- 396 ns bunch spacing
- 36 colliding bunches
- $1.7 \cdot 10^6$ bunch collisions per second
- many bunch collisions contain multiple interactions

Tevatron: the B_s factory



CDF II

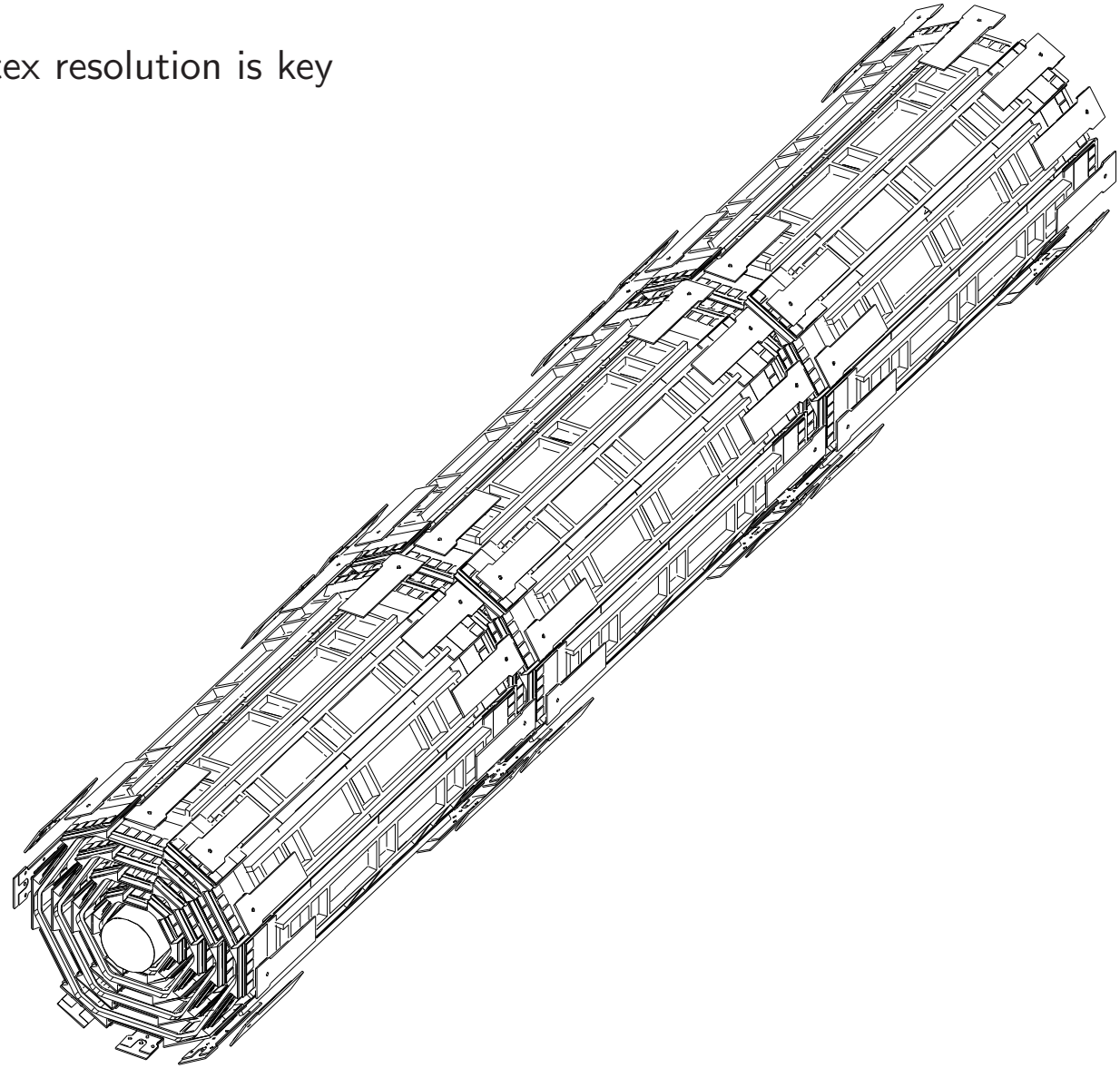
- general-purpose detector
- physics results in many areas: top, EW (+ Higgs searches), B, QCD, exotics searches



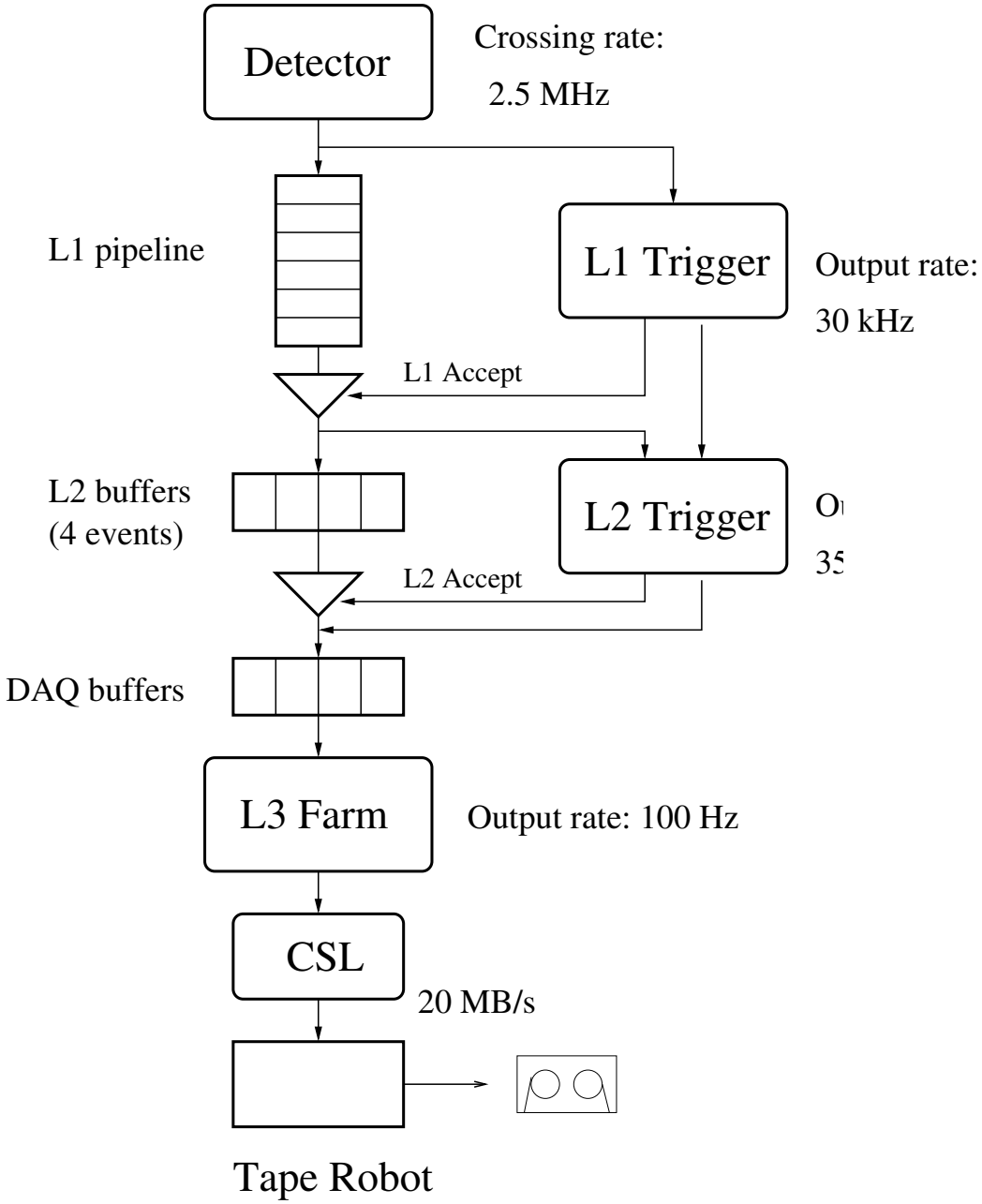
SVX

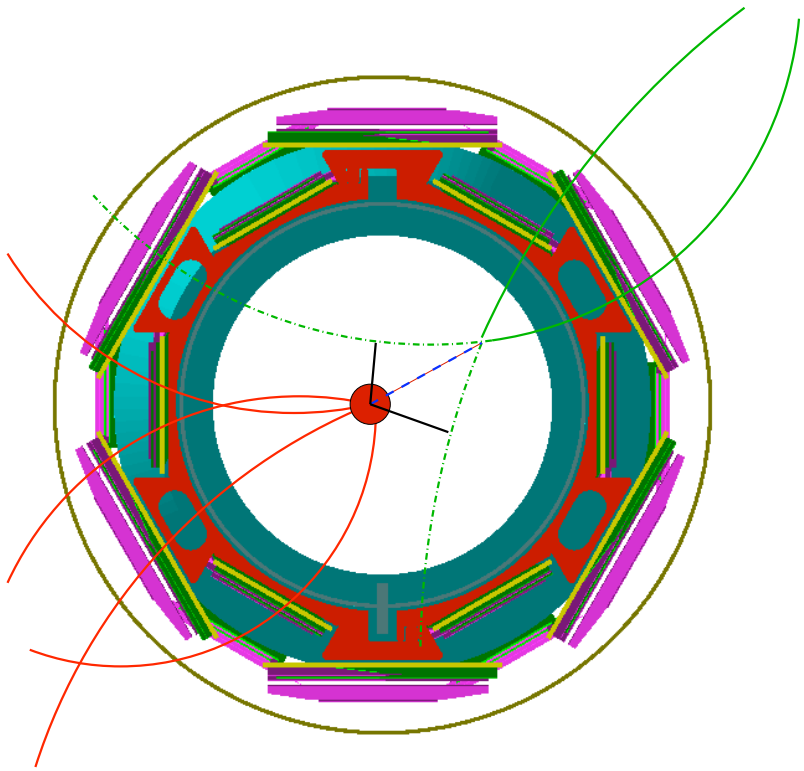
Background rejection relies on $c\tau(B) \sim 500\ \mu$m

Good vertex resolution is key



CDF trigger


Detector
Crossing rate:
2.5 MHz
L1 pipeline
L1 Trigger
Output rate:
30 kHz
L1 Accept
L2 buffers
(4 events)
L2 Trigger
L2 Accept
DAQ buffers
L3 Farm
Output rate: 100 Hz
CSL
20 MB/s
Tape Robot

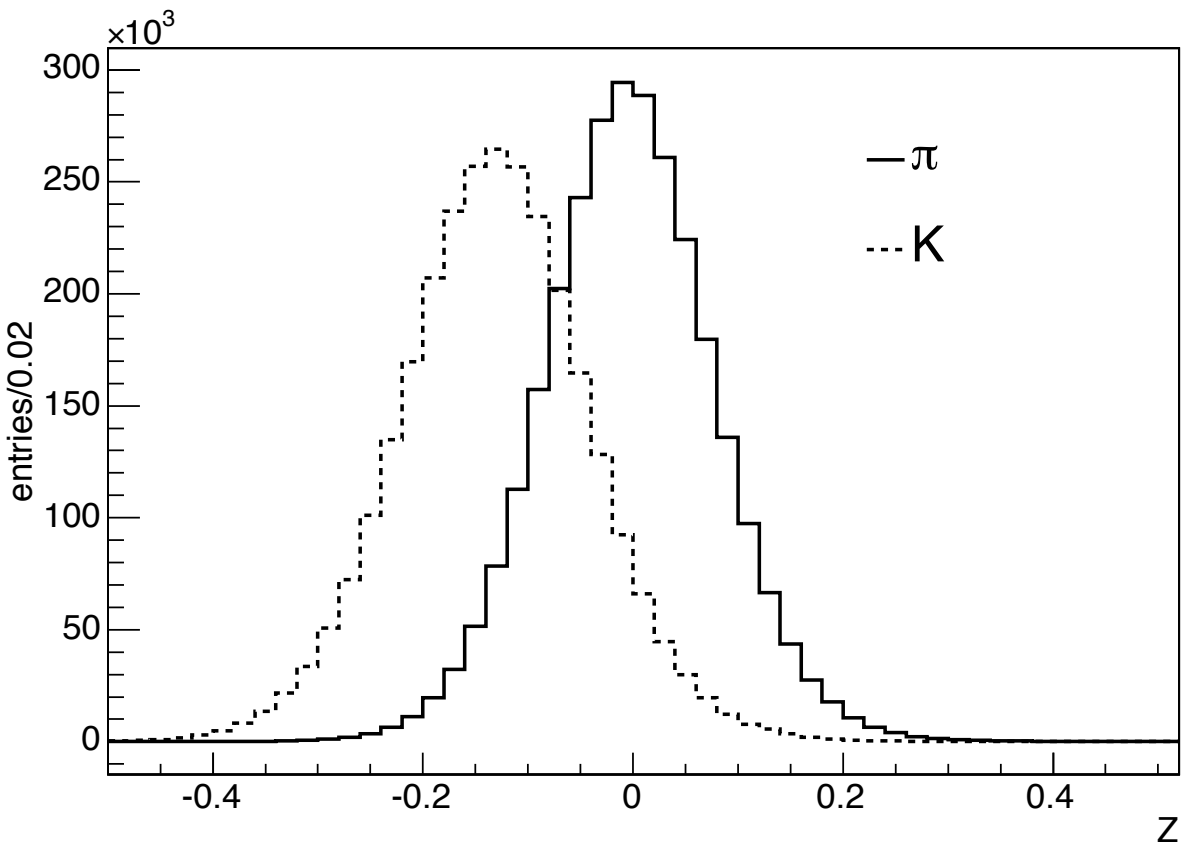


CDF dE/dx PID

We use gaussian-distributed $Z = \log\left(\frac{dE/dx(\text{measured})}{dE/dx(\text{expected for } \pi)}\right)$ as PID variable

K–π separation:

$$\frac{\langle Z_\pi \rangle - \langle Z_K \rangle}{\sigma_Z} = \frac{130 \cdot 10^{-3}}{90 \cdot 10^{-3}}$$



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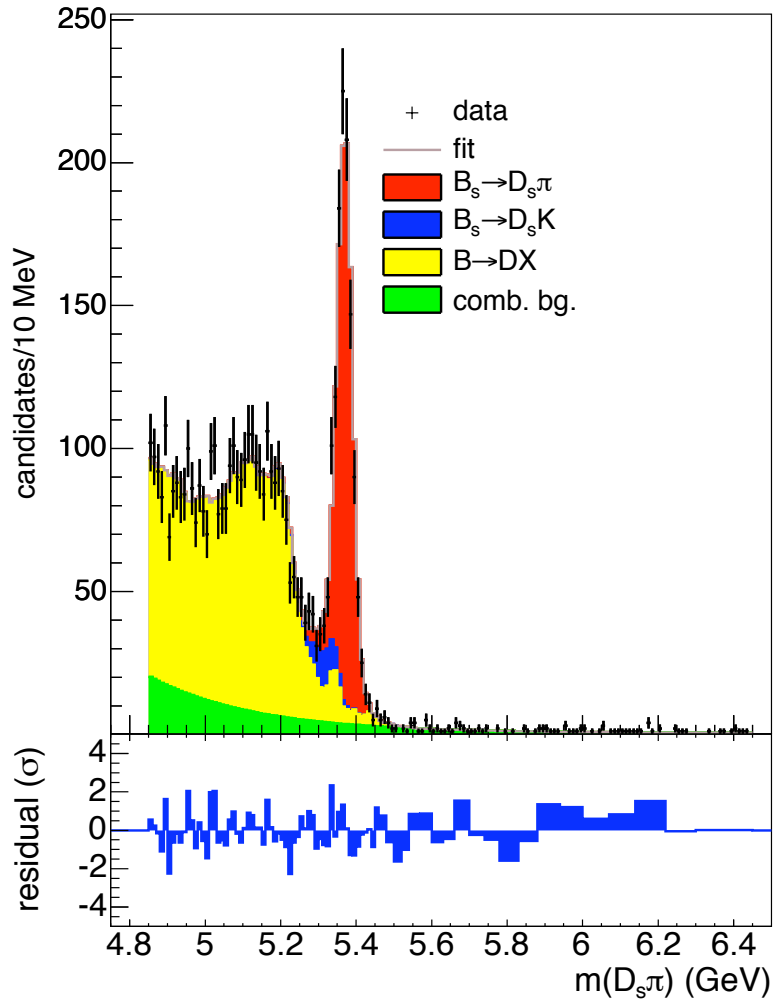
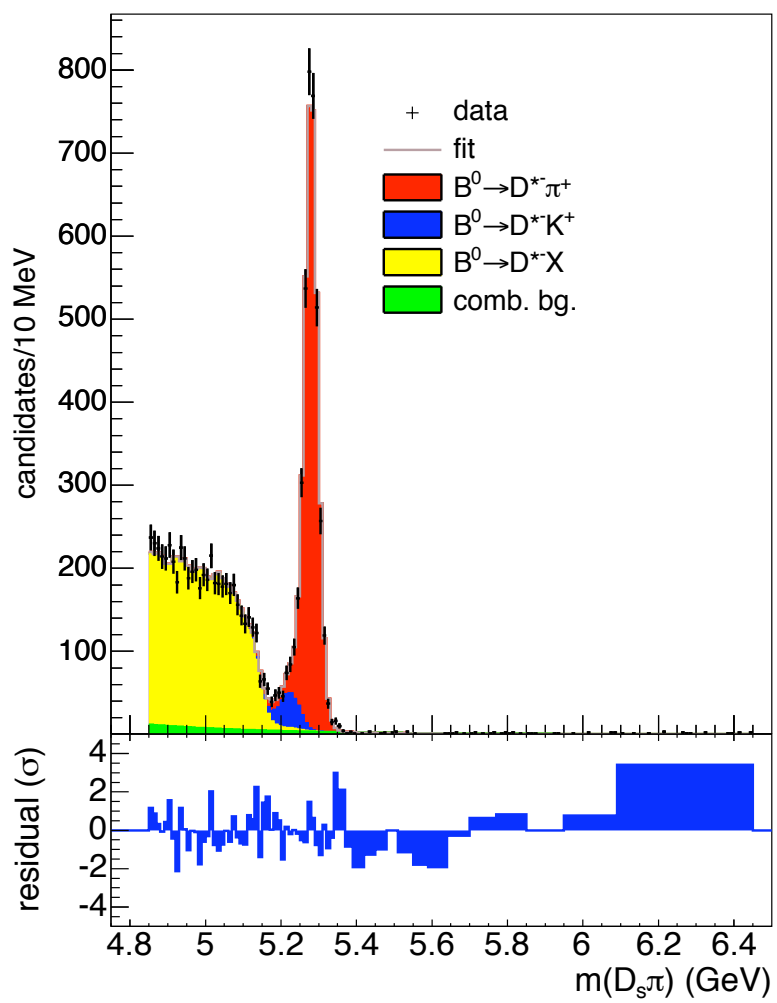
Event selection

Vertexing (in 3D) to cut out short-lived background

Narrow resonances help! We use 1.2 fb^{-1} of $D_s^+(\phi(K^+K^-)\pi^+)X$ data





Fit in mass and dE/dx

Fit in $m(D_s\pi)$ and $Z = \log\left(\frac{dE/dx(\text{measured})}{dE/dx(\text{expected for } \pi)}\right)$

K–π separation is 1.4σ $\Rightarrow$ no event-by-event PID cut

Maximum-likelihood fit

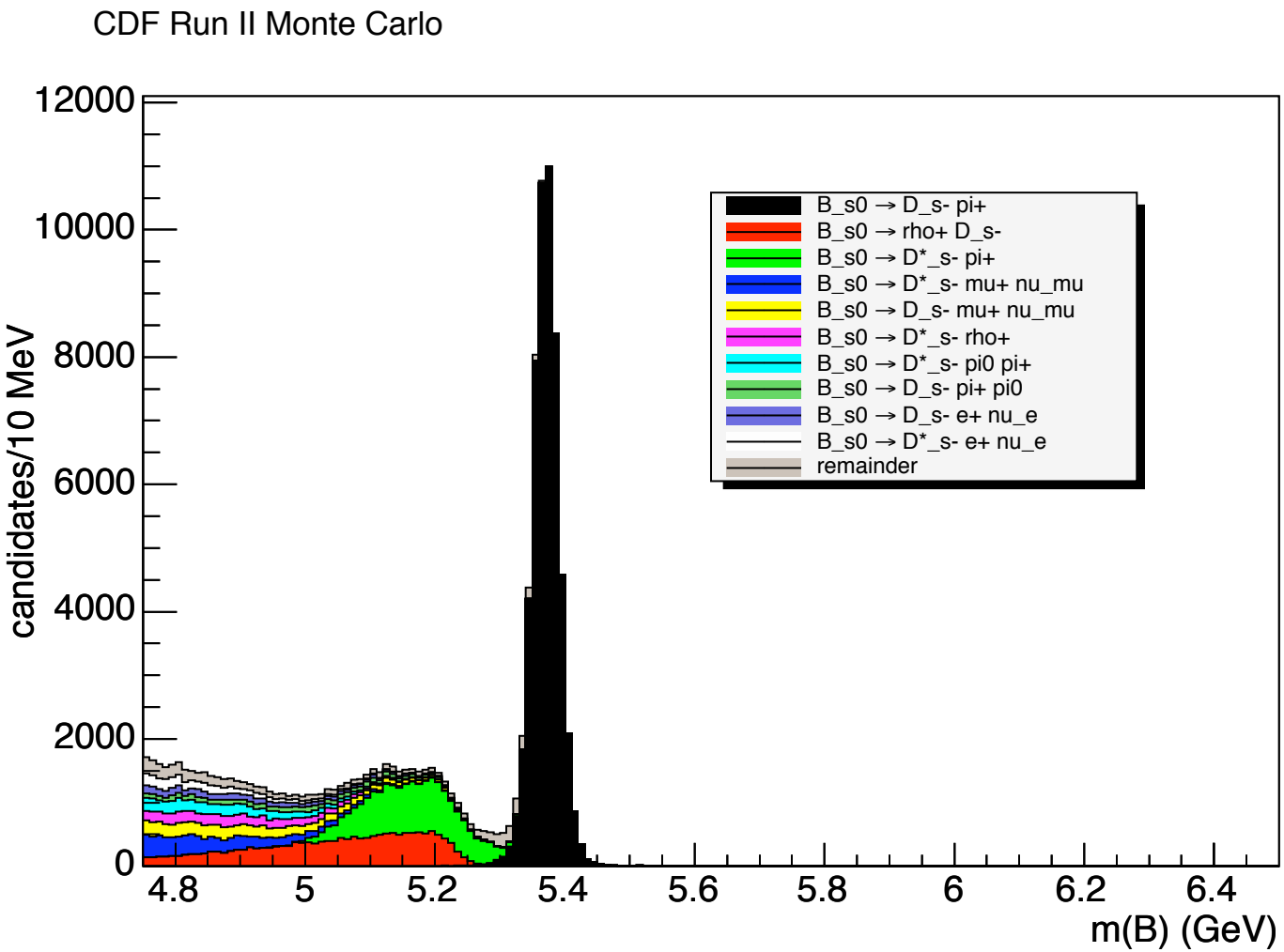
$$L(f_1, \ldots, f_{M-1}) = \prod_{i=1}^{N} \sum_{j=1}^{M} f_j \, p_j(m_i) \, q_j(Z_i), \quad \text{where } f_M = 1 - \sum_{j=1}^{M-1} f_j$$

Fit ingredients:

- N candidates
- M components
- f_j fraction of candidates in the j-th component
- $p_j(m)$ is the mass pdf of the j-th component
- $q_j(Z)$ is the Z pdf

Component types:

- single-B ($B \to D\pi$, $B \to DK$, $B \to D^*\pi$, . . .)
- fake D + track combinatorial background
- real D + track combinatorial background



- high-statistics MC samples
- shapes are difficult to parameterize

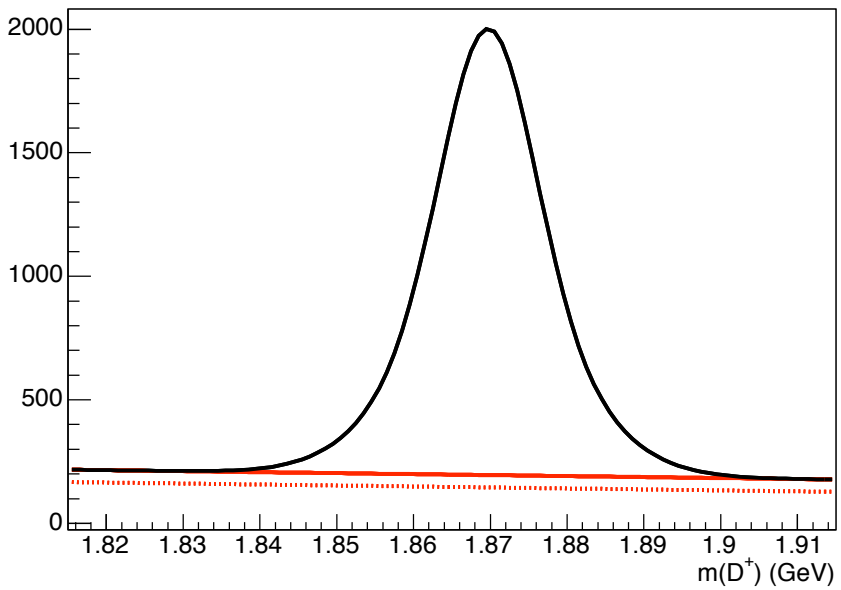
  $\Rightarrow$ use histograms as mass pdf's

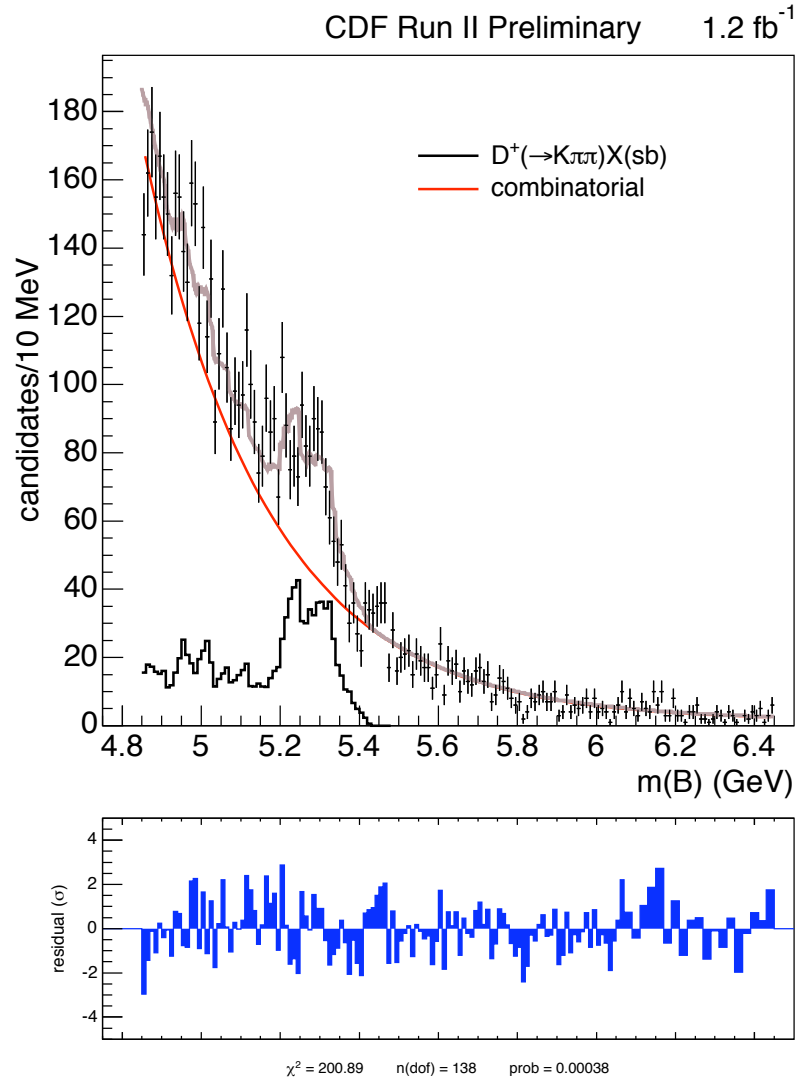
Special treatment for radiative tail $B \to D\pi(n\gamma)$

$\Rightarrow$ use PHOTOS for shape, but let normalization float

Combinatorial background

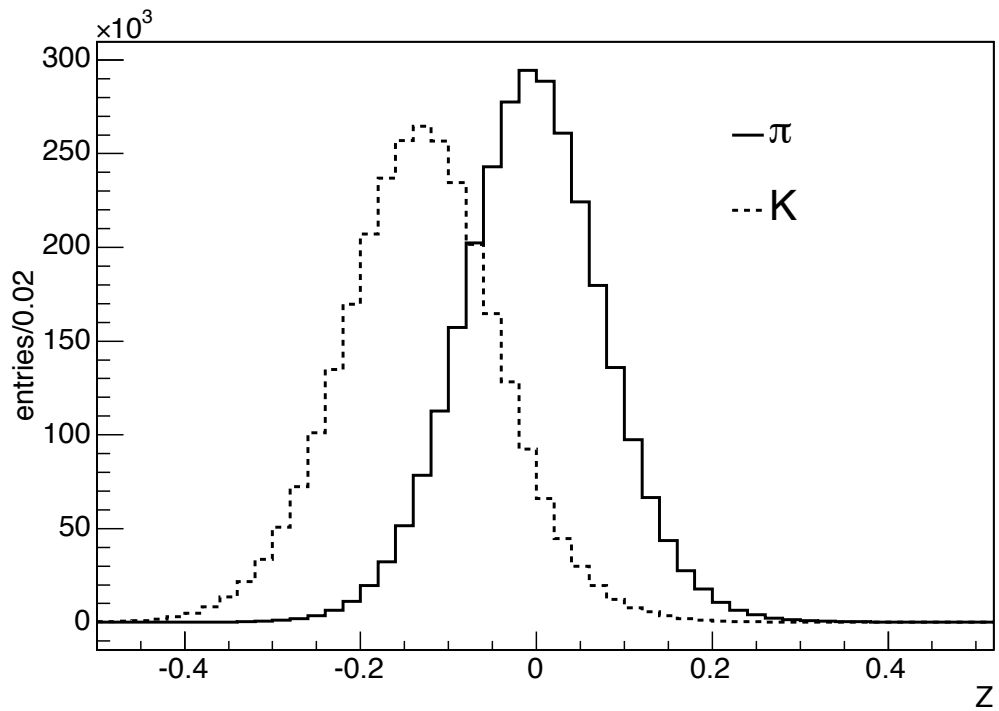
- real-D + track background is taken from wrong-sign ($D_s^+\pi^+$) sample
- fake-D + track background is taken from D sidebands
  - but there is also poorly reconstructed real D from B in the sideband region





dE/dx templates

- $B \to D\pi(X)$, $B \to DK(X)$ components:
  - Z template from prompt $D^{*+} \to D^0(K^-\pi^+)\pi^+$ (3M events)
  - standard hit-based + track-based calibrations
  - additional correction for local tracking chamber activity (5% level)
- $B \to De\nu$ components:
  - parametric dE/dx simulation
- fake-D combinatorial:
  - Z template taken from D sideband
  - "signal subtraction" performed to remove real-D leakage
- real-D combinatorial:
  - Z template taken from WS data



All Z pdf's are histograms

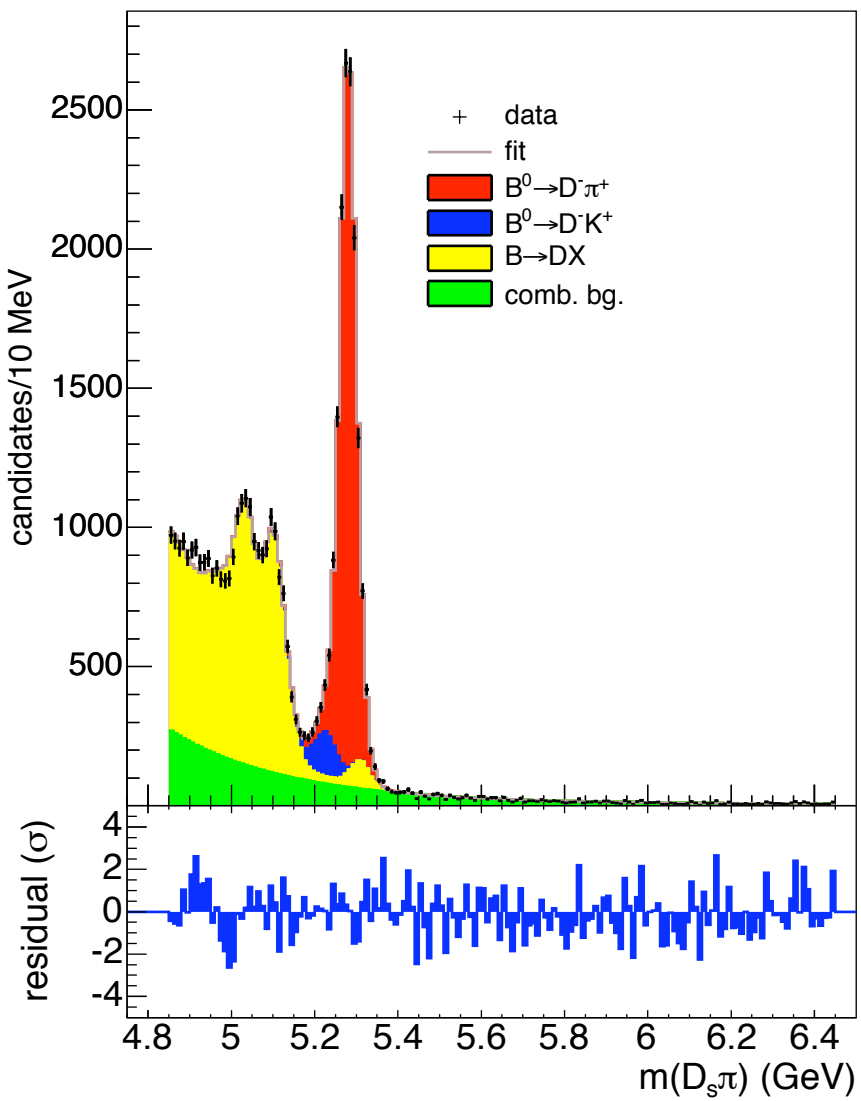
Fit configuration

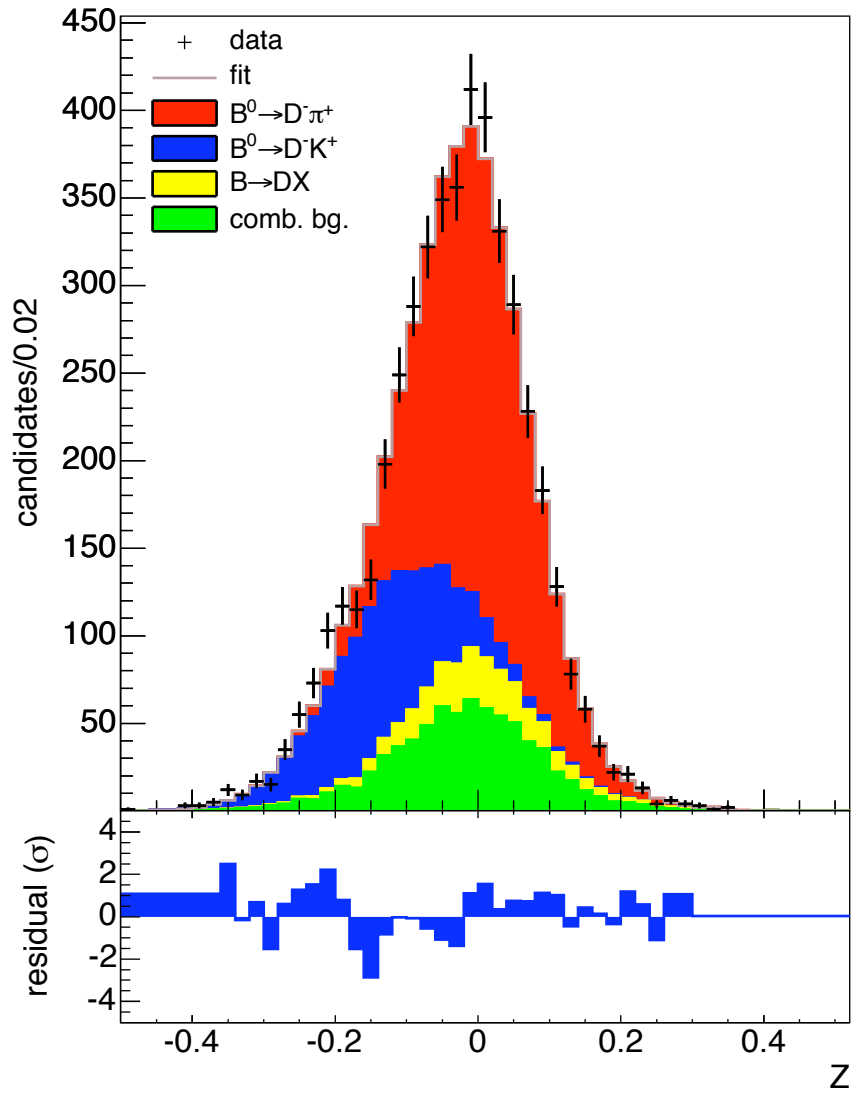
Decay modes	Mass pdf	dE/dx pdf	fit parameters
$B_s \to D_s\pi$	MC	prompt $D^* \to \pi$, $s:p$ reweight	norm floating
$B_s \to D_s\pi(n\gamma)$	MC	prompt $D^* \to \pi$, $s:p$ reweight	norm floating
$B_s \to D_s K$	MC	prompt $D^* \to K$, $s:p$ reweight	norm floating
$B_s \to D_s\rho$	MC	prompt $D^* \to \pi$, $s:p$ reweight	norm floating
$B_s \to D_s^*\pi$	MC	prompt $D^* \to \pi$, $s:p$ reweight	norm floating
$B^0/B^+ \to D^+X$	MC	species fractions from MC	norm floating
$B_s \to D_s^{(*)}K^{(*)}$	MC	prompt $D^* \to K$, $s:p$ reweight	norm fixed to $B_s \to D_s^{(*)}X$
$B_s \to D_s^{(*)}eX$	MC	parametric e simulation	norm fixed to $B_s \to D_s^{(*)}X$
$B_s \to D_s^{(*)}X$	MC	species fractions from MC	norm floating
$B^0 \to D_s^{(*)}K$	MC	prompt $D^* \to K$, $s:p$ reweight	norm fixed to $B^0 \to D_s^{(*)}\pi$
$B^0 \to D_s^{(*)}\pi$	MC	prompt $D^* \to \pi$, $s:p$ reweight	norm floating
$\Lambda_b \to \Lambda_c X$	MC	species fractions from MC	norm floating
combinatorial bg	D_s^+ SB	D_s^+ SB	norm $= 1 - \sum_i f_i$, shape fixed

$\overline{B}^0 \to D^+ X$ control sample

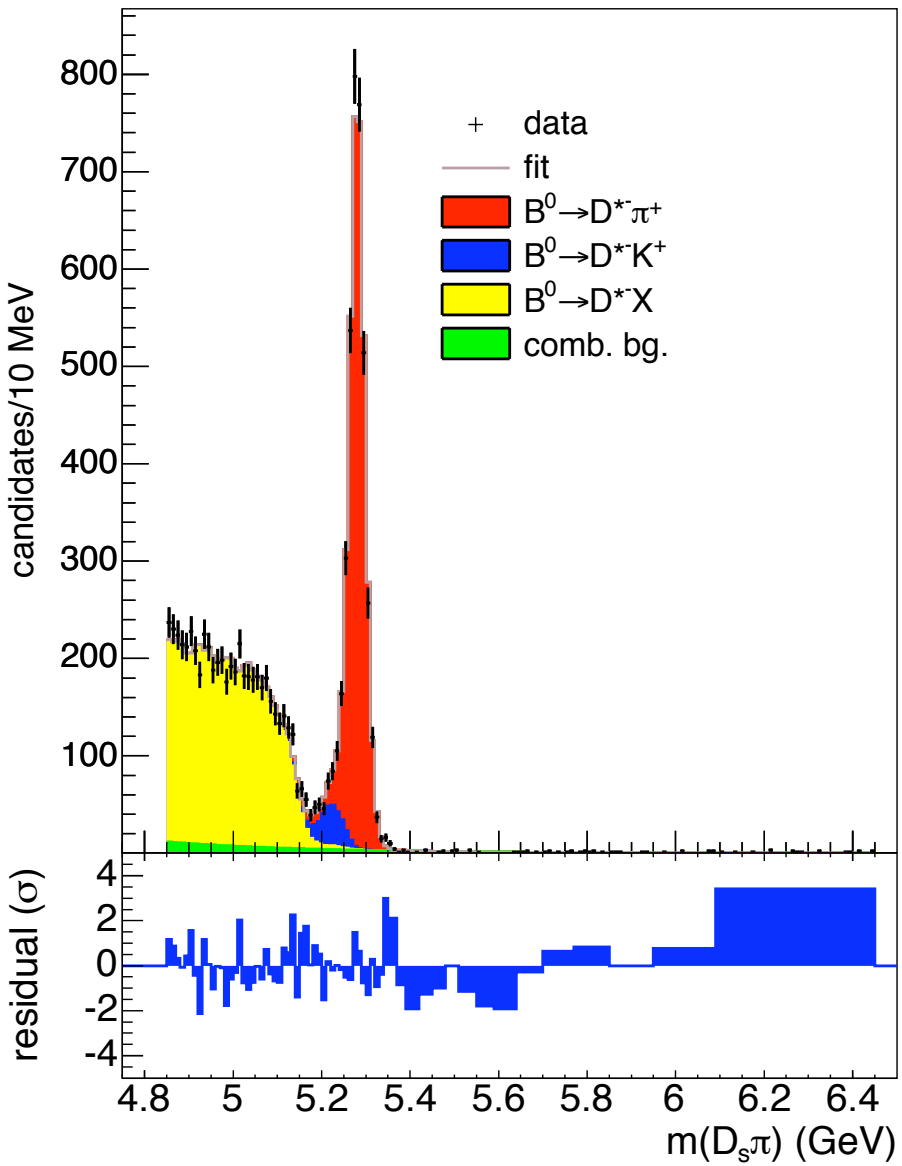
2 control samples!

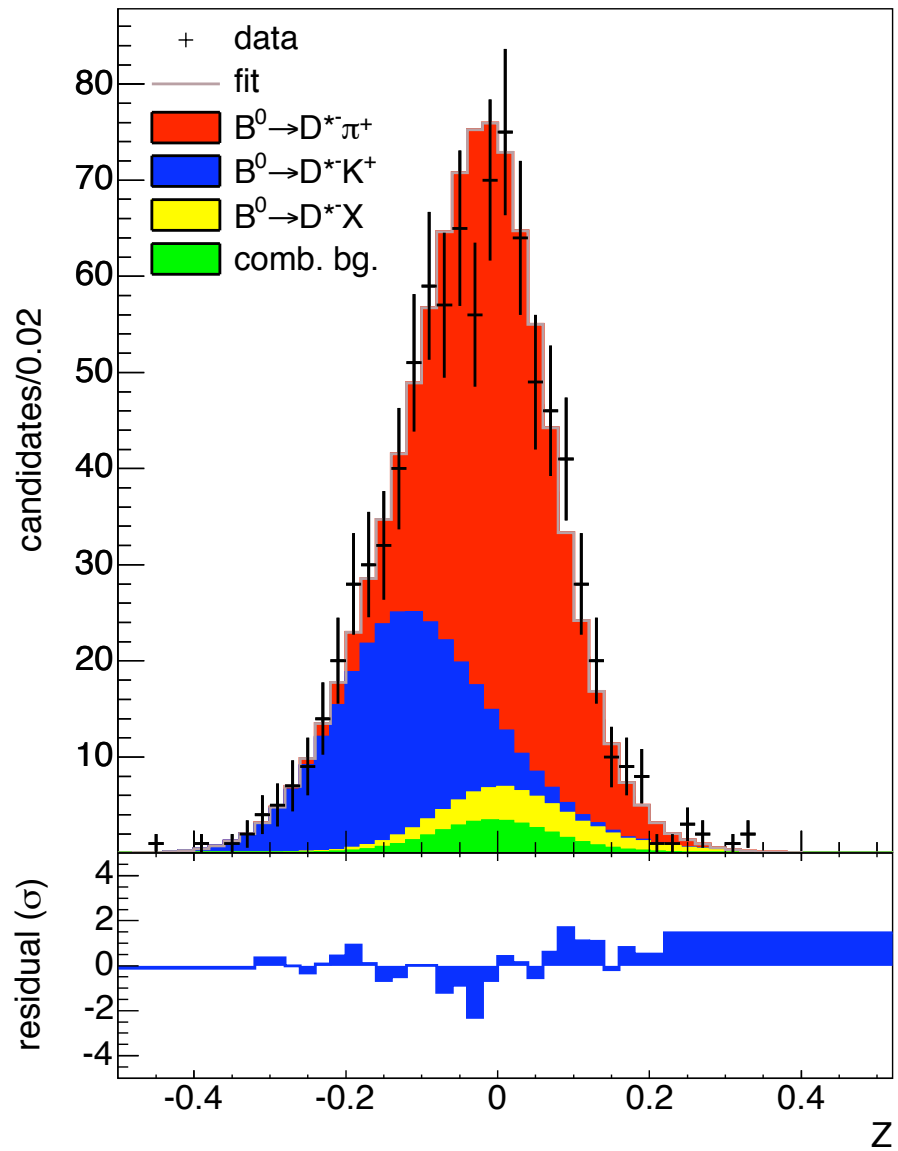
- develop analysis on these (including systematics evaluation)
- compare with world average





$\overline{B}^0 \to D^{*+}X$ control sample



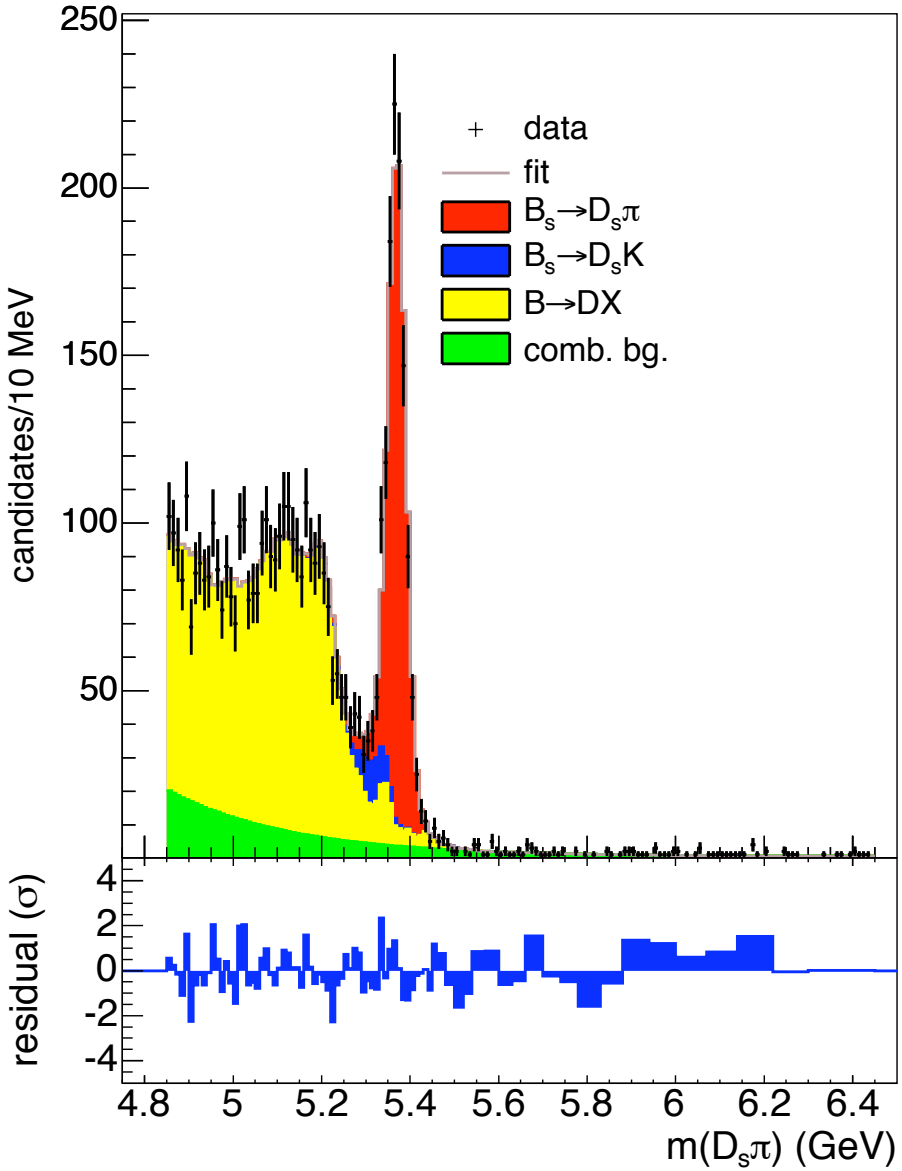


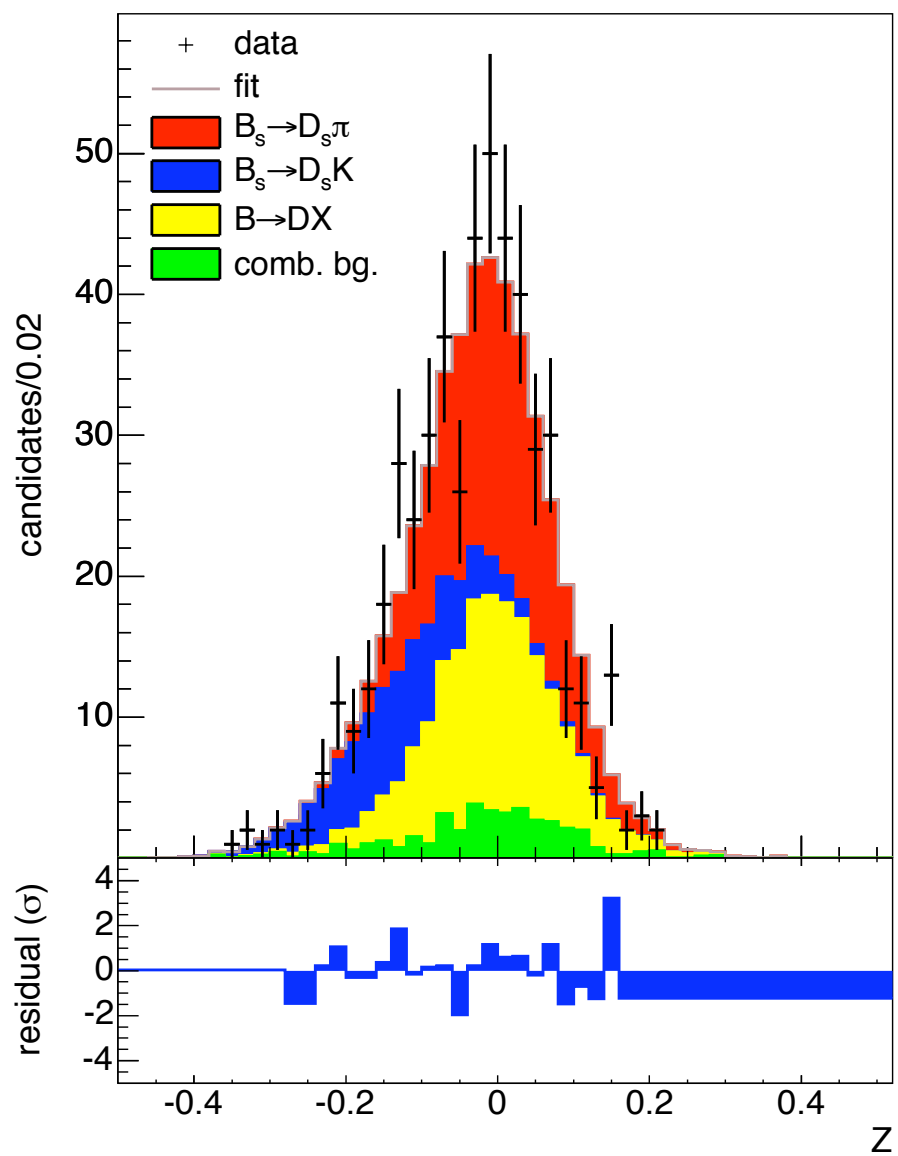
Control samples

Sample	$D^+K^-/D^+\pi^-$ (%)	$D^+\rho^-/D^+\pi^-$	$D^{*+}\pi^-/D^+\pi^-$
PDG 2008	6.80 ± 1.66	2.21 ± 0.68	0.81 ± 0.22
our measurement	8.61 ± 0.52 (1.04σ)	2.38 ± 0.15 (0.24σ)	1.13 ± 0.07 (1.37σ)
	$D^{*+}K^-/D^{*+}\pi^-$ (%)	$D^{*+}\rho^-/D^{*+}\pi^-$	
PDG 2008	7.76 ± 0.45	2.46 ± 0.38	
our measurement	7.99 ± 0.75 (0.26σ)	2.93 ± 0.15 (1.15σ)	

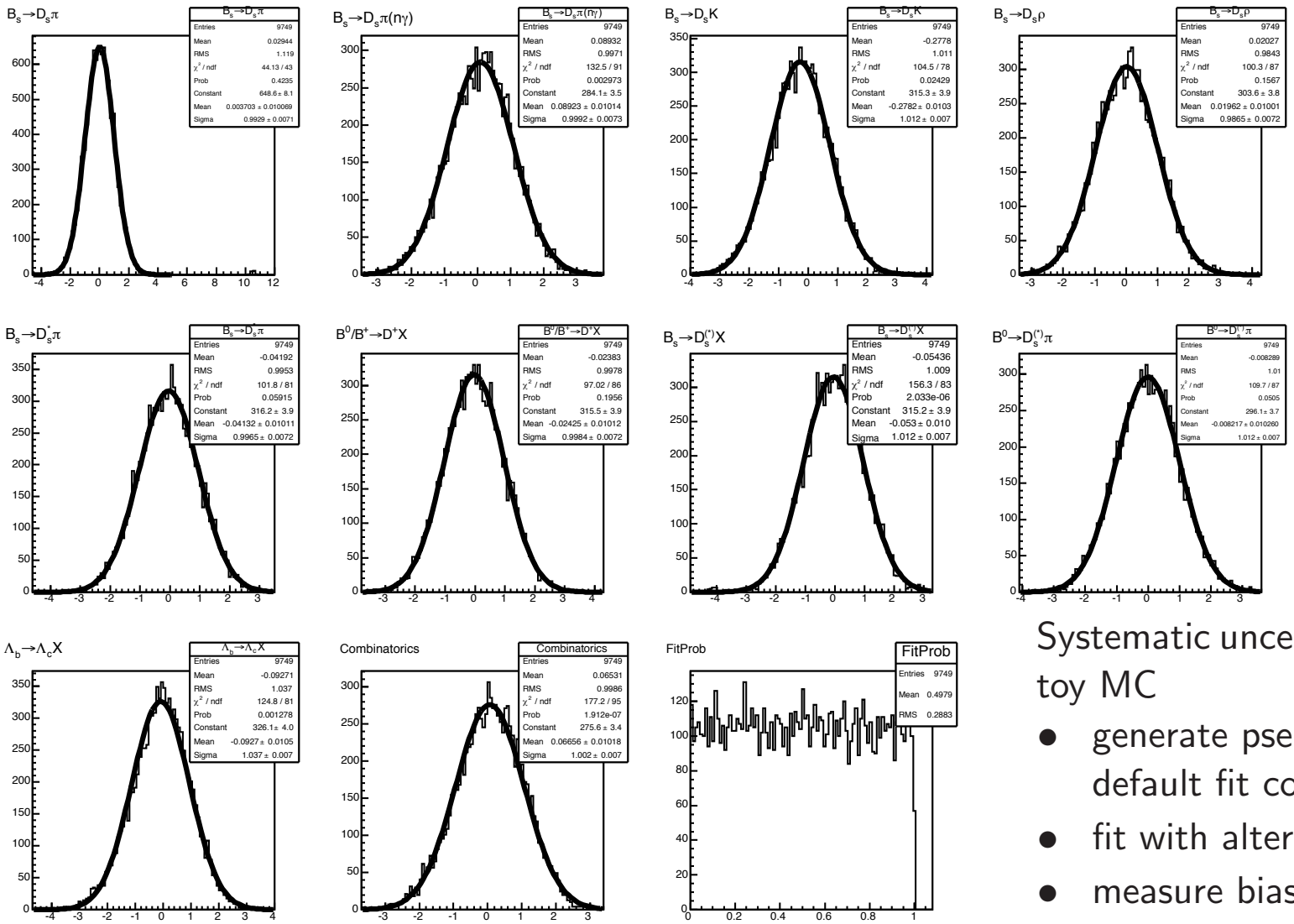
- quoted errors are statistical only
- systematic uncertainty on $D^+K^-/D^+\pi^-$ is 0.70%
- the control samples agree to better than 2σ

$\overline{B}_s^0 \to D_s^{\pm}(\phi\pi^{\pm})X$ signal sample





Systematic uncertainty evaluation



Systematic uncertainties are studied with toy MC

- generate pseudoexperiments with default fit configuration
- fit with alternate model
- measure bias in 10^4 pseudoexperiments

Systematic uncertainties

Source	Systematic uncertainty
dE/dx pdf modeling	0.007
Mass pdf modeling	0.004
Combinatorial-background model	0.002
Fitter bias due to finite statistics	0.001
Sum in quadrature	0.009

Biggest systematic uncertainties come from modeling of dE/dx

- differences between template and physics sample are corrected for
- higher-order effects remain

Note: some of the biggest uncertainties (reflections, radiative tails) are treated as statistical uncertainties

Result

First measurement of $\mathcal{B}(\overline{B}_s^0 \to D_s^\pm K^\mp)/\mathcal{B}(\overline{B}_s^0 \to D_s^+ \pi^-)$:

$$\mathcal{B}(\overline{B}_s^0 \to D_s^\pm K^\mp)/\mathcal{B}(\overline{B}_s^0 \to D_s^+ \pi^-) = 0.097 \pm 0.018(\text{stat}) \pm 0.009(\text{sys})$$

with a statistical significance of 8.1σ for the $\overline{B}_s^0 \to D_s^\pm K^\mp$ signal

Where can we go with $\mathcal{O}(102)$ $\overline{B}_s^0 \to D_s^\pm K^\mp$ events?

Sample behaves statistically like 30 events

γ through mixing

- penalty from flavor tagging: $\times$ 5%
- penalty from rapid oscillations: $\times\mathcal{O}(1)$

γ through CP states

- penalty from $\tanh(\Delta\Gamma\, t/2)$: $\times$ 5–10%
- but systematic uncertainty due to $\Delta\Gamma$ input

CDF can

- include $D_s^+ \to \overline{K}^{*0}(K^-\pi^+)K^+$ ($\times$ 2 statistics)
- include new data ($\times$ 4 statistics)
- use new theoretical prediction on size of radiative tail in $B \to D\pi$ decays
- constrain size of D^+ and Λ_c reflections
- constrain D_s mass to central value
- use $\Delta\Gamma$ measurements from the Tevatron
- for a gain of $\times$ 2–8 in statistical power

Conclusion

- We have made the first observation of $\overline{B}_s^0 \to D_s^\pm K^\mp$
- We have performed the first measurement of $\mathcal{B}(\overline{B}_s^0 \to D_s^\pm K^\mp)/\mathcal{B}(\overline{B}_s^0 \to D_s^+ \pi^-)$
- This is the first step towards measuring γ in $\overline{B}_s^0 \to D_s^\pm K^\mp$ decays
- A paper has been posted on the arXiv[7] and submitted to PRL

  $\Rightarrow$ we're waiting for the response to our response to the referees' questions

[7] T. Aaltonen *et al.* [CDF Collaboration], arXiv:0809.0080 [hep-ex].

Your eyes will be opened to a world
full of beauty, charm, and adventure.
Lucky Numbers: 24, 15, 36, 28, 49, 30

Bonus slides

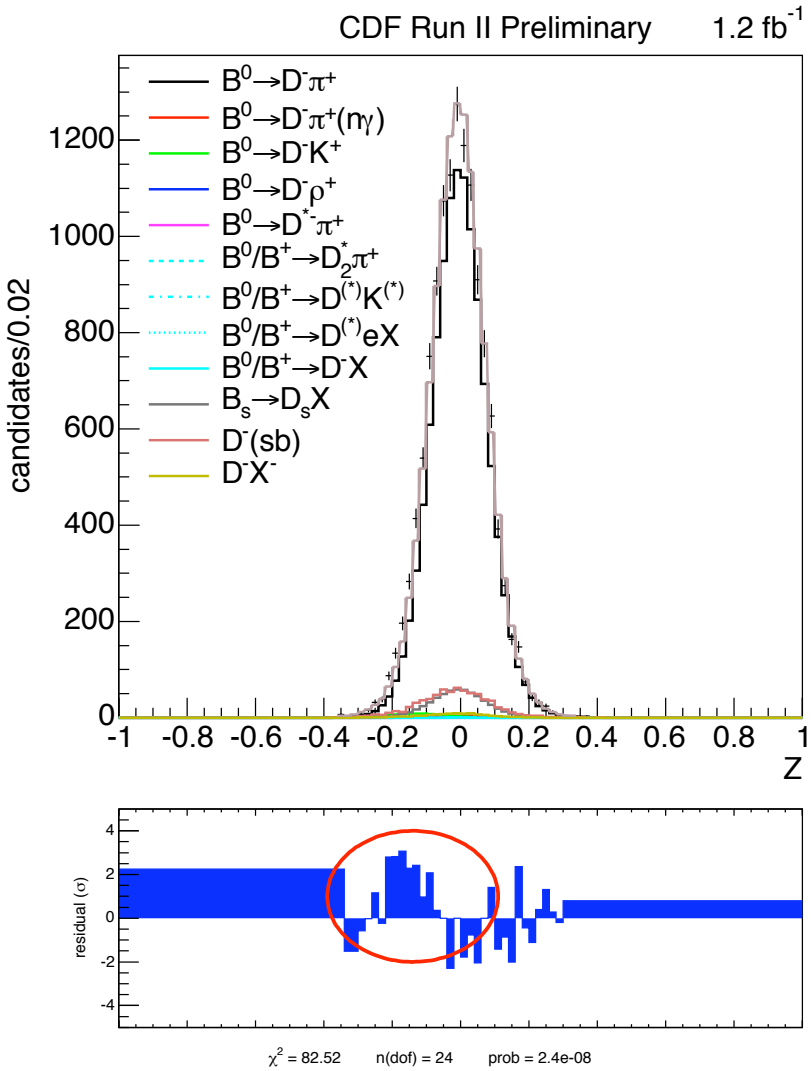
Event selection

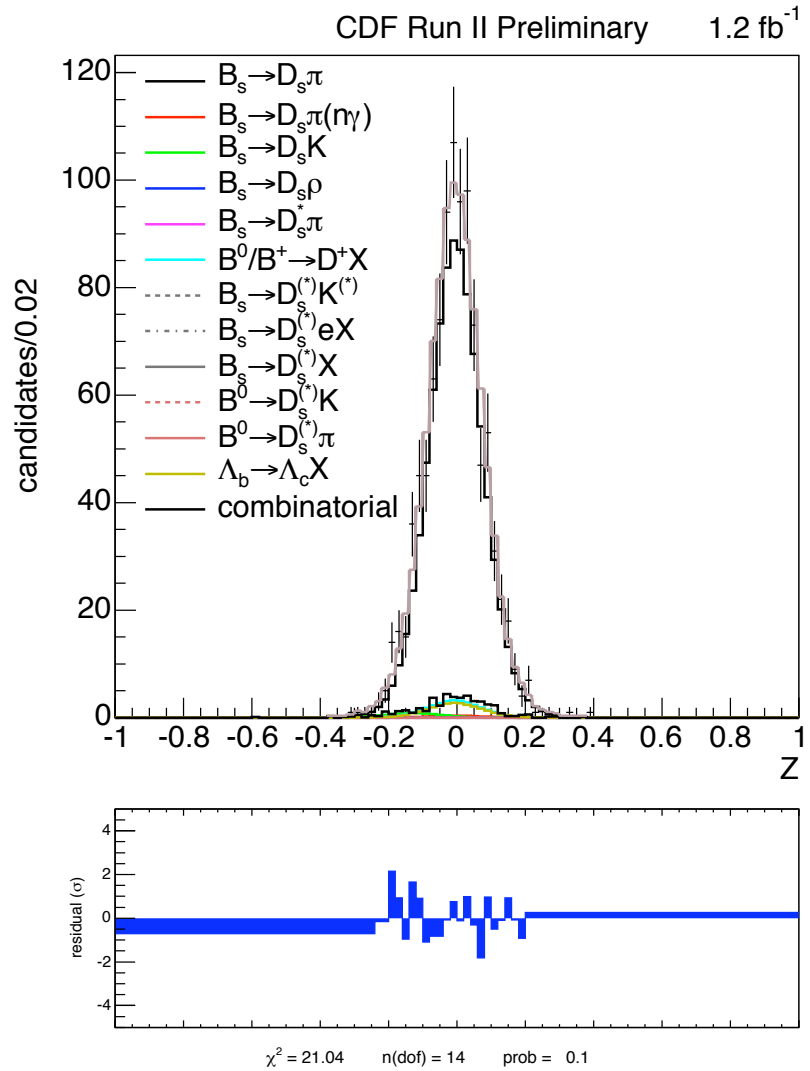
	$B^0 \to D^-(K^+\pi^-\pi^-)X$	$B_s^0 \to D_s(\phi\pi)X$
$\chi^2_{xy}(B)$	< 10	< 10
$\chi^2_{xy}(D)$	< 15	< 15
$L_{xy}(B)/\sigma_{L_{xy}}(B)$	> 8	> 8
$L_{xy}(B \leftarrow D)$	> 0	> 0
$\lvert d_0(B)\rvert$	$< 60\ \mu$m	$< 60\ \mu$m
$p_{\mathrm{T}}(B)$	> 5.5 GeV	> 5.5 GeV
$p_{\mathrm{T}}(\pi_B)$	> 2.0 GeV	> 2.0 GeV
$\Delta R(D, \pi_B)$	< 1.5	< 1.5
$\lvert z_0(B)/\sigma_{z_0}(B)\rvert$	< 3	< 3
iso(B) $(\Delta R < 1)$	> 0.5	> 0.5
$m(D^+)$	$\lvert m/\mathrm{MeV} - 1869.4\rvert < 20$	
$m(D_s^+)$		$\lvert m/\mathrm{MeV} - 1968.3\rvert < 20$
$m(\phi)$		$1013 < m/\mathrm{MeV} < 1028$
π_B SVT match distance	< 25	< 25
π_B SVT χ^2	< 15	< 15
π_B SVT p_{T}	> 2 GeV	> 2 GeV
$m(K, \pi \mapsto p, \pi)$	$\lvert m/\mathrm{MeV} - 2285\rvert > 250$	
$m(K\pi\pi) - m(K\pi)$	$\Delta m/\mathrm{MeV} > 180$	$\Delta m/\mathrm{MeV} > 180$
Good run list	SVX, SVT	SVX, SVT

Systematic uncertainties

Most unsettling effect: residual discrepancy in π Z template

Effect is not actually visible in $D_s(\phi\pi)X$ sample





Complete list of systematic uncertainties

Effect	$D_s^{\pm}K^{\mp}/D_s^{+}\pi^{-}$ uncertainty (%)
K template Z shift	0.59
Statistical fluctuations in the mass templates	0.35
Signal subtraction in fake-D Z template	0.29
Statistical uncertainty on Z shift	0.24
Composition of $D^{+}X$ Z template	0.21
Combinatorial bg model	0.18
MC mass scale factor	0.18
MC mass smearing	0.13
Composition of $\Lambda_c X$ Z template	0.11
Fitter bias due to finite statistics	0.09
Sample dependence of Z shift	0.07
Sum in quadrature	0.87