The Center for Accelerator and Particle Physics
at the Illinois Institute of Technology

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Hadron Collider Charm Physics Reach

Daniel M. Kaplan

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“High-Impact” Charm Physics

- Charm decay sensitive to possible New Physics via searches for
  - rare FCNC decays
  - mixing
  - CP violation

  processes to which Standard Model contributions are highly suppressed

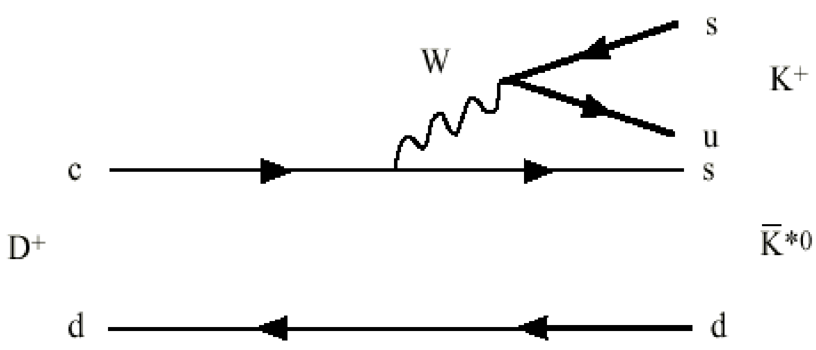
$\Rightarrow$ possible “low-background windows” to phenomena at high mass scales

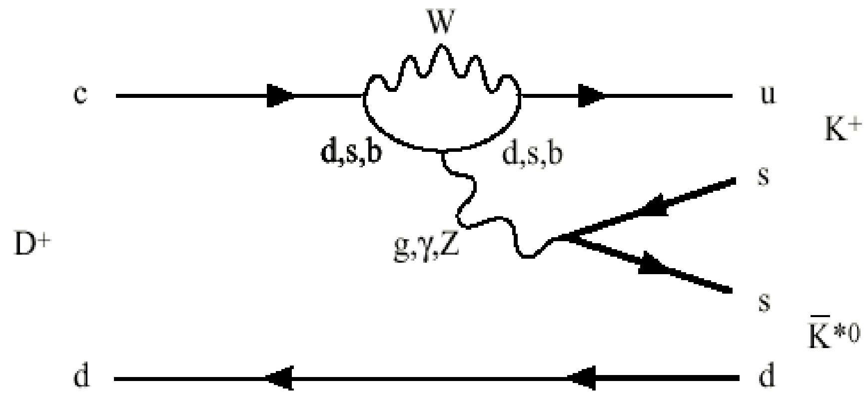
"High-Impact" Charm Physics (cont'd)

- Conventional wisdom:
  - High-impact charm physics a longshot
- *BUT:*
  - Despite impressive success of KM model for $C\!\!\not{P}$,
    - Far from clear that KM mechanism is *sole* source of $C\!\!\not{P}$
    - Indeed, baryon asymmetry of Universe suggests there are additional sources
- Searching for small NP signatures on top of large SM effects is complicated and challenging!
- Given large SM "background" in B $C\!\!\not{P}$, how can non-KM contributions best be detected?
  - One suggestion:

Charm CP violation

- Charm decay expected to violate CP in Standard Model due to interference of trees with Penguins:





– SM charm $C\!\!\!/P$ only for singly Cabibbo-suppressed (SCS) modes

  - Depending on final-state phases, can be $\mathcal{O}(10^{-3})$ in some modes
    [see e.g. F. Buccella et al., Phys. Rev. D 51, 3478 (1995)]

– SM charm $C\!\!\!/P$ absent in CF & DCS modes

⇒ Any observation of charm $C\!\!\!/P$ in CF or DCS modes, or at $> \mathcal{O}(10^{-3})$ in SCS modes, would be clear evidence for New Physics

Charm CP violation – Beyond Standard Model

- Charm $C\not{P}$ *can* occur (due to exchange of heavy particles in loops) at up to $O(10^{-2})$ in many SM extensions, e.g.:
  - Multi-Higgs (incl. some SUSY) models
  - Models with leptoquarks
  - Left-right-symmetric models

[see e.g. Y. Nir, hep-ph/9911321;
I. I. Bigi, hep-ph/9412227;
S. Pakvasa, hep-ph/9408270;
W. Buchmuller and D. Wyler, Phys. Lett. 177B, 377 (1986)
and Nucl. Phys. B268, 621 (1986);
M. Leurer, Phys. Rev. Lett. 71, 1324 (1993);
A. Le Yaouanc, L. Oliver, and J.-C. Raynal, Phys. Lett. B292 (1992) 353;
T. G. Rizzo, Int. J. Mod. Phys. A 4, 5401 (1989);
K. S. Babu et al., Phys. Lett. B205, 540 (1988).]

Estimating Hadron Collider Charm Sensitivities

- Difficult at this point – can be done only very approximately:

1. Collider charm cross sections so far measured only in limited regions of phase space
2. Charm sensitivity is complicated - depends on
   - reconstruction and PID efficiency for each mode
   - D* tagging efficiency for neutral modes
   - vertex cuts that optimize signal/background
   - details of analysis technique
3. Future B experiments have not yet studied it in detail

⇒ To compare experiments, I will use (overly) simple benchmarks:

estimated # charm and $D^0 \rightarrow K^- \pi^+$ produced, reconstructed

in lieue of detailed simulation studies yet to be carried out,
and consider statistical sensitivity only

(but systematics tend to scale with statistics)

Use CP violation as first example...

Previous & Current Charm Samples:

1. **FNAL E687,**[1] **E791,**[2] **FOCUS,**[3] **and CLEO II**[4] have comparable $C\not{P}$ reach, and are averaged in PDG '01:

1. P. L. Frabetti et al., Phys. Rev. D 50, 2953 (1994).
2. E. M. Aitala et al., Phys. Lett. B403 (1997) 377; Phys. Lett. B421 (1998) 405.
3. J. M. Link et al., Phys. Lett. B485, 20 62 (2000).
4. J. Bartelt et al., Phys. Rev. D 52, 4860 (1995).

- PDG2001 world averages:

CP-violation decay-rate asymmetries

$$A_{CP}(K^+K^-\pi^\pm) = -0.017 \pm 0.027$$
$$A_{CP}(K^\pm K^{*0}) = -0.02 \pm 0.05$$
$$A_{CP}(\phi\pi^\pm) = -0.014 \pm 0.033$$
$$A_{CP}(\pi^+\pi^-\pi^\pm) = -0.02 \pm 0.04$$

$$A_{CP}(K^+K^-) = 0.026 \pm 0.035$$
$$A_{CP}(\pi^+\pi^-) = -0.05 \pm 0.08$$
$$A_{CP}(K^0_S\phi) = -0.03 \pm 0.09$$
$$A_{CP}(K^0_S\pi^0) = -0.018 \pm 0.030$$
$$A_{CP}(K^\pm\pi^\mp) = 0.02 \pm 0.20$$

	# charm		# $D^0\to K\pi$		δA_{CP}
exp't	prod.	reconst.	prod.	reconst.	typ.
FNAL E687		0.8×10^5			≈ 0.1
FNAL E791	$\approx10^8$	2.5×10^5	1.2×10^6	3.7×10^4	≈ 0.05
CLEO II	2.7×10^6		1.0×10^6	1.8×10^4	≈ 0.05
FOCUS		$\approx10^6$		1.0×10^5	≈ 0.03

Previous & Current Charm Samples (cont'd)

2. B-Factories:

(Not hadron colliders, but set the scale for competition)

$$\sigma_{c\bar{c}} = n_c \frac{4\pi\alpha^2}{3s} q^2 = 1.0 \text{ nb}$$

$\mathcal{L} = 3 \times 10^{33} \Rightarrow 3 \times 10^7$ charm produced $/10^7$ s

$\Rightarrow \delta A_{CP} \approx 0.01$?

Already, $\exists$ published BELLE result (limit on $D^0 \to K\pi/KK$ lifetime difference) based on 2×10^5 $D^0 \to K\pi$ (few times FOCUS) from 23 fb^{-1}

Of course, upgrades are planned: 1 $ab^{-1} \to 10^7$ $D^0 \to K\pi \to \delta A_{CP} \approx 0.003$?

Comments on Hadron Colliders vs. B Factories

- Hadron Collider advantage:
  - Relative cross sections:

Hadron Collider	B Factory
$\sigma_{c\bar{c}} \sim 10\sigma_{b\bar{b}}$	$\sigma_{c\bar{c}} \approx \sigma_{b\bar{b}}$

- Hadron Collider challenge:
  - How to trigger efficiently on charm with acceptable trigger rate?

Beauty triggers:

high-p_t secondaries, large impact parameters

...less efficient for charm

Future Experiments:

1. COMPASS:

- FT combined charm/DIS experiment now being commissioned at CERN SPS

  Project 7×10^4 $D^0 \rightarrow K\pi$ reconst. (comparable to FOCUS)

2. HERA-B:

- High-p_t triggers not optimal for charm, but sensitivity estimated as a few times FOCUS [Collins, Goulart, Schwartz HERA-B memo]

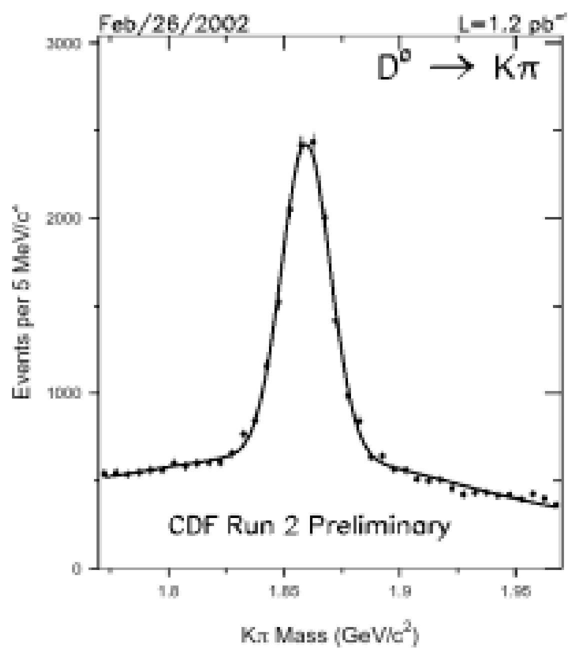
3. CDF:

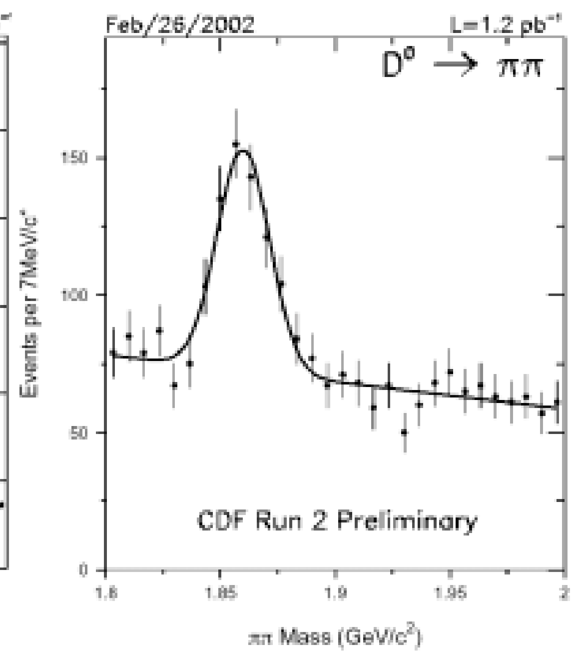
- Run II SVT gives high, but acceptable, trigger rate, with track requirements

  $p_t > 2$ GeV/c
  $b > 100$ μm

  $\Rightarrow$ Run IIa (~2 fb^{-1}) $\rightarrow$

  ~ 10^7 $D^0 \rightarrow K\pi$?
  (if trigger rate continues acceptable as **L** rises;
  prompt fraction not yet known but believed large)





Future Experiments (cont'd)

4. LHC*b* :

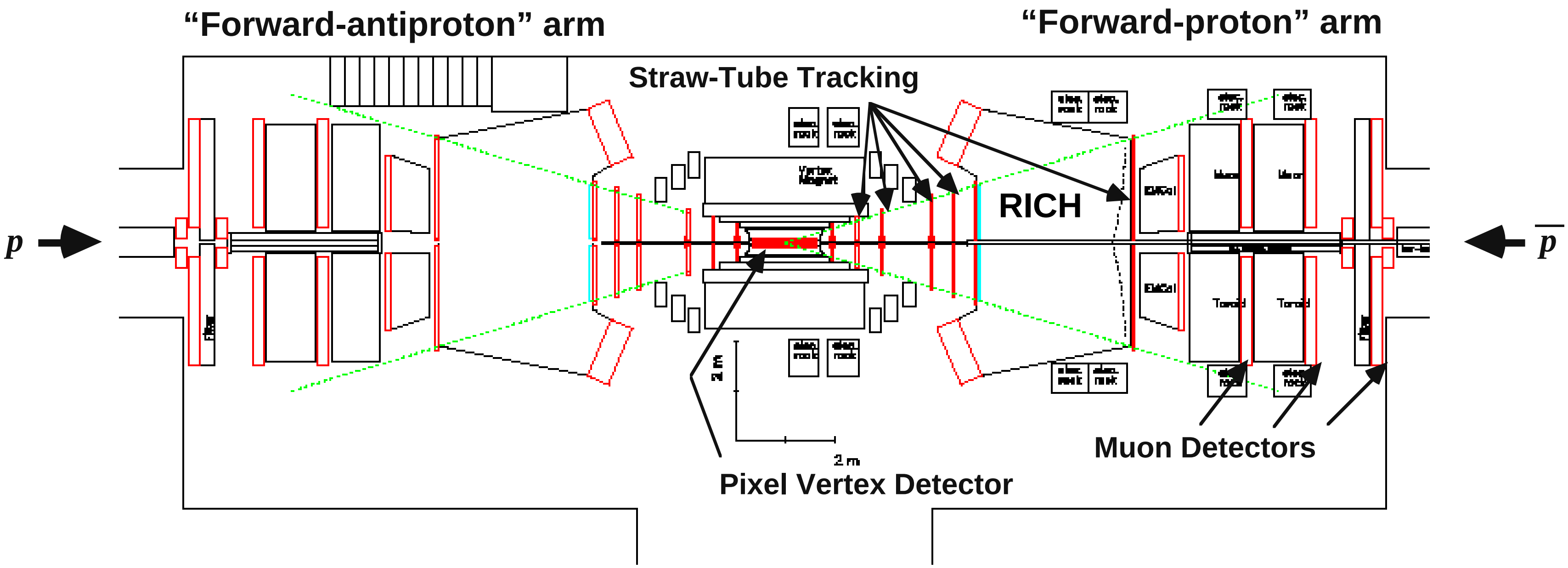
- Charm cross section rising logarithmically ⇒ ≈ ×2 from Tevatron to LHC energy
  - but increase mainly at experimentally-inaccessible small angles
- Detector background rates (multiplicity per event) also increasing logarithmically

  ⇒vertex detectors need to be farther from beam to avoid radiation damage
- High-p_t hadron triggers not optimal for charm
- Moderate-p_t lepton triggers may give good sensitivity for FCNC dimuon modes

5. BTeV:

- A new Tevatron experiment dedicated to the study of CP violation, mixing, and rare decays of *b* and *c* hadrons – turn-on expected ≈2007

Key Features of BTeV:



- Fast-readout, rad-hard silicon pixel detectors near beam
  → (2 x 6 mm)-square beam hole
- Level-1 displaced-vertex trigger
- Fast RICH particle ID
- $PbWO_4$ EM cal → fast, rad-hard, superb resolution
- Forward geometry → excellent vertex resolution: $\delta\tau \approx 30$ fs typ.
  → excellent particle ID

- Can run with wire target in halo
  → early apparatus shakedown
  → trigger and calibration studies
  → charm physics

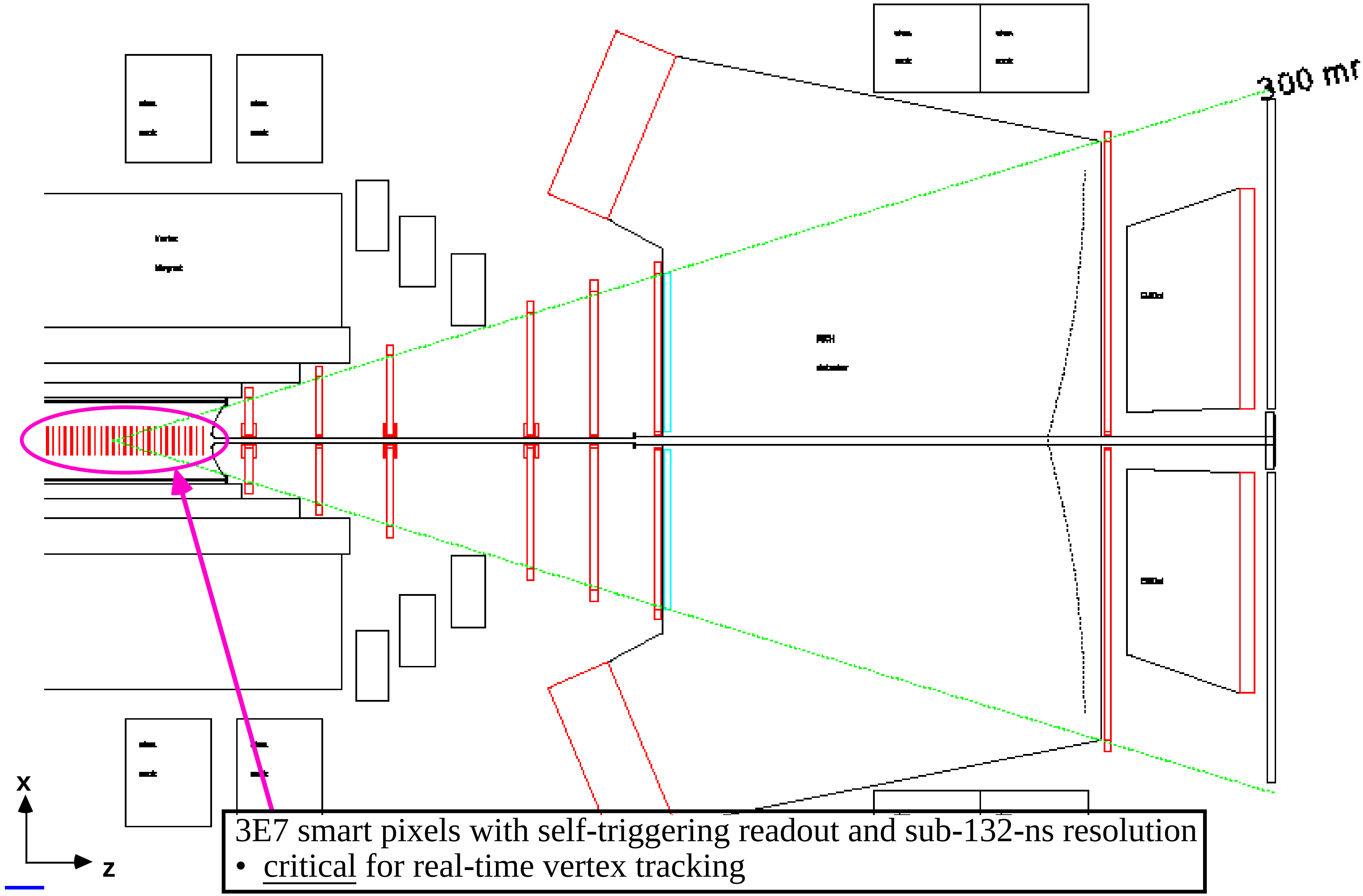
BTeV Trigger Philosophy:

- Events of interest:
  - not only e.g. $B_d \to J/\psi\ K_S$ (have final-state high-p_t leptons)
  - also e.g. $B_s \to D_s^+ K^-$, $B_d \to \rho^0 \pi^0$,
    and $D^{*+} \to D^0\pi^+$, $D^0 \to K^-\pi^+$ (no final-state leptons)

$\Rightarrow$ Best to trigger on characteristics common to all heavy-quark decays:

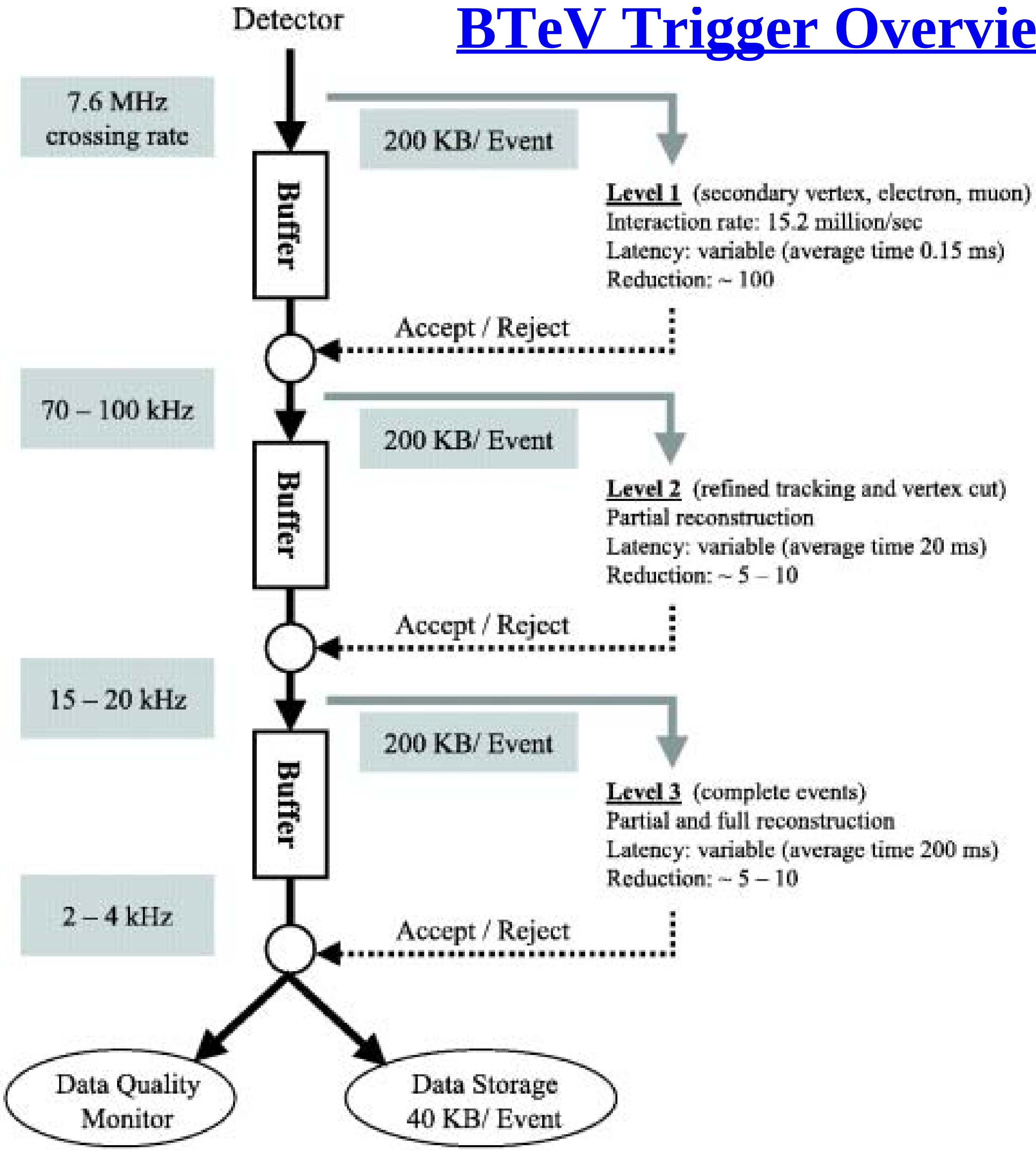
$\to$ Separated production and decay vertices

Zoomed View of 1 Arm:



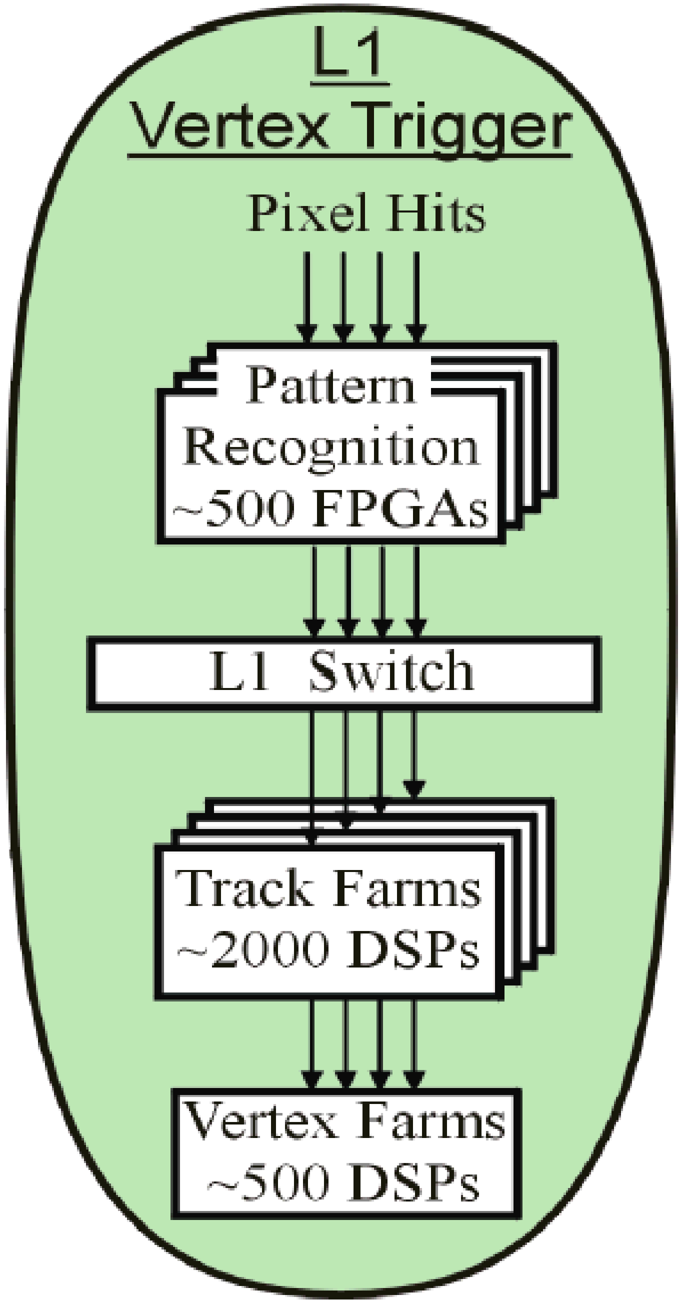
3E7 smart pixels with self-triggering readout and sub-132-ns resolution
• critical for real-time vertex tracking

BTeV Trigger Overview



- No pretrigger!
- Find tracks and search for 2ndary vertices in every beam crossing
  - Pipeline must accept a new event every 132 ns on average

Level 1 Vertex Trigger Block Diagram:

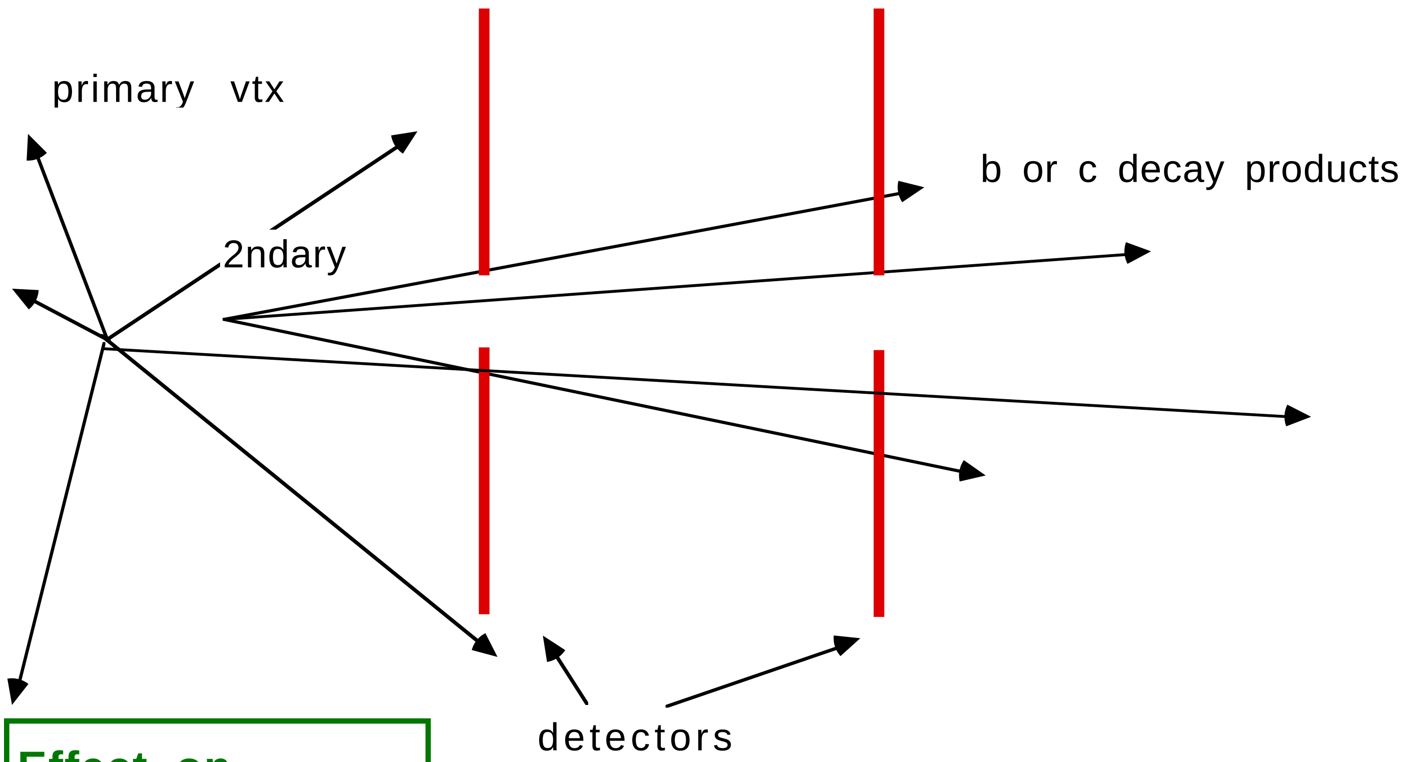


- Massively-parallel arrays of programmable elements:

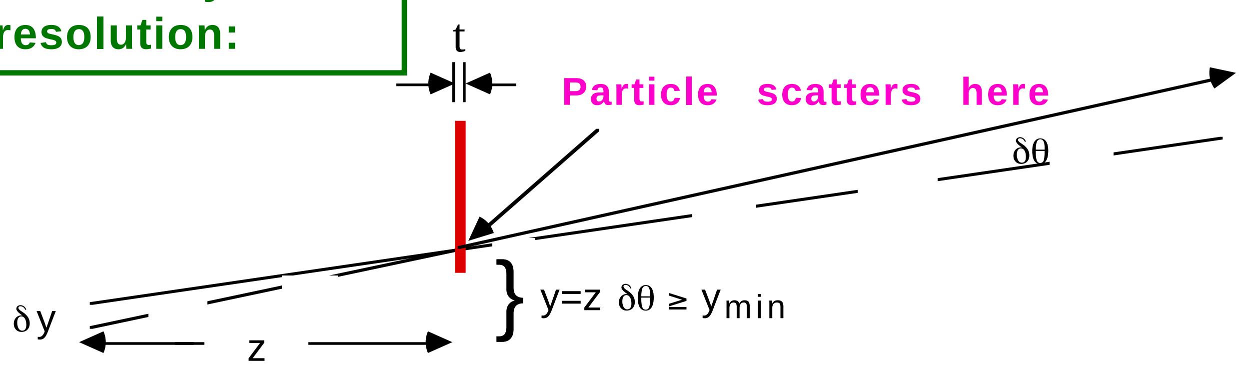
"FPGA tracker"

"DSP tracker"

Importance of Distance from Beam:



Effect on secondary-vertex resolution:



$$\delta\theta \approx \frac{0.015GeV}{p}\sqrt{\frac{t}{X_0}}$$

$$\delta y \approx z\delta\theta$$

$$\approx y_{\min}\left(\frac{0.015GeV}{p_\perp}\sqrt{\frac{t}{X_0}}\right)$$

Comparing CDF, BTeV, and LHC*b* :

	CDF (Run IIa)	**BTeV**	**LHC*b***	**unit**
Geometry	central	forward	forward	
Design L	8×10^{31}	2×10^{32}	2×10^{32}	$cm^{-2}\ s^{-1}$
Arms	—	2*	1	
Trig p_t-min	2	~ 0.5	several	GeV/c
Trig b-min	~100 μm	several σ	?	
SVD r-min	2.4†	0.6	1	cm

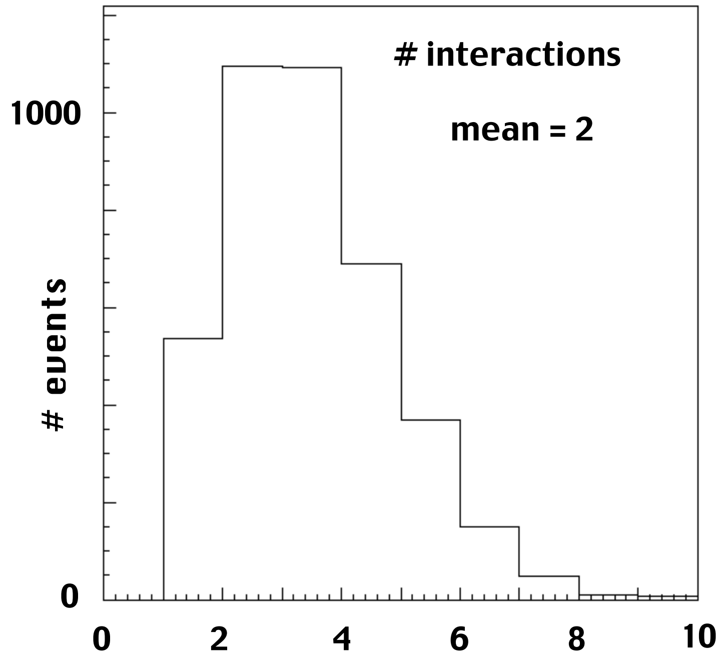
*1 initially with possible upgrade to 2

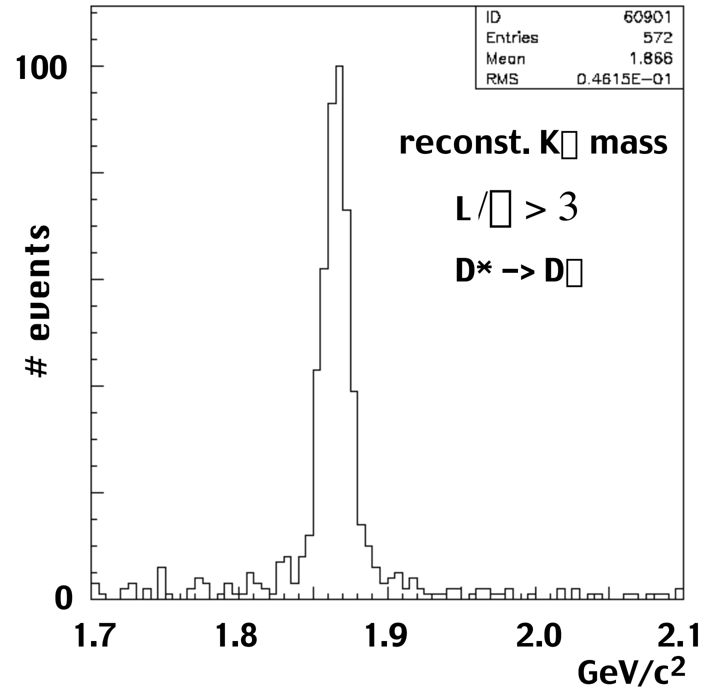
†beam pipe at 1.67 cm

- Note central rapidity is only ≈20% of produced D mesons

BTeV Charm Sensitivity

- Full Geant simulation of 4000 charm events (J. Butler, H. Cheung):





- $D^0 \to K\pi$ efficiency ≈1% (including ≈10% assumed vertex-trigger efficiency)

(Collider mode)

These results preliminary – still need to understand and optimize charm efficiency of "BB33" trigger algorithm

Sensitivity Comparison:

	CDF	BTeV	
		FT	Coll.
Running time Luminosity Interaction rate D^0 ($\overline{D}^0$) / int. $A^{0.29}$ $B(D^0 \to K\pi)$	2.5×10^7 s 8×10^{31} 1% ? 3.85%	10^7 s $2 \times 10^6\ s^{-1}$? $6.5 \times 10^{-4}\ A^{0.29}$ 2 – 4.5 (C – W) 3.85%	10^7 s 2×10^{32} $1.5 \times 10^7\ s^{-1}$ 1% ? 1 3.85%
$D^0 \to K\pi$ produced		**$(1 - 2.3) \times 10^9$**	**6×10^{10} ?**
Acceptance Trigger eff. Reconst. eff.		35% 14 – 22% 38%	27%* 11%* 42%
$D^0 \to K\pi$ reconst.	**10^7**	**$(2.0 - 7.0) \times 10^7$**	**7×10^8 ?**
CP reach	**2×10^{-3} ?**	**1×10^{-3} ?**	**3×10^{-4} ?**

(All estimates preliminary!)

*older MCFast calculation

- CP reach approaching 1×10^{-4} may be possible in multi-year BTeV run

$\Rightarrow$ Even SM $C\!\!\!/P$ may be measurable

→ Similar charm sensitivities (within order of magnitude) in collider and fixed-target modes:

- Collider per-nucleon cross section $\uparrow \times \approx 10 - 20$, can make up $\times \approx 2 - 4$ from A-dependence:

$$\sigma_{charm} \propto A^1$$
$$\sigma_{total} \propto A^{0.71}$$

- FT int. rate assumed limited by pile-up in p_t trigger – can do better?

  (HERA-B demonstrated 30 MHz)

- Collider trigger efficiency $\downarrow \times \approx 10$?

→ still need to study trigger optimizations

Some Interesting Rare Decays

- Selected FCNC modes & limits:

	BR limit	Exp't	SM*	/Rp*	CDF†	BTeV†
D^0 modes						
e^+e^-	$< 6.2 \times 10^{-6}$	E791	10^{-23}	1.0×10^{-10}	$\sim 10^{-6}$	$\sim 10^{-7}$
$\mu^+\mu^-$	$< 4.1 \times 10^{-6}$	BEATRICE	3.0×10^{-13}	3.5×10^{-6}	$\sim 10^{-6}$	$\sim 10^{-7}$
D^+ modes						
$\pi^+e^+e^-$	$< 5.2 \times 10^{-5}$	E791	2.0×10^{-6}	2.3×10^{-6}	$\sim 10^{-6}$	$\sim 10^{-7}$
$\pi^+ \mu^+\mu^-$	$< 1.5 \times 10^{-5}$	E791	1.9×10^{-6}	1.5×10^{-5}‡	$\sim 10^{-6}$	$\sim 10^{-7}$
$\pi^+ \mu^+e$	$< 3.4 \times 10^{-5}$	E791	0	3.0×10^{-5}	$\sim 10^{-6}$	$\sim 10^{-7}$

*SM & R-parity-violating-SUSY predictions from Burdman, Golowich, Hewett, Pakvasa, hep-ph/0112235

†future-experiment guestimates based on crude scaling of E791 by $\sqrt{N}$

‡R-parity-violating-SUSY already constrained by experimental limit

Conclusions:

- With new SVX and SVT, CDF is doing better than expected in charm
  - competitive with B factories
  - shows hadron-collider experiments can do charm physics
- In late 200X's BTeV could surpass CDF charm sample by $\mathcal{O}(10^2)$
- Charm $C\!\!\!/P$ sensitivity $\mathcal{O}(10^{-4})$ possible $\Rightarrow$ may observe SM effects
- Rare decays could confirm R-parity-violating SUSY – already significantly constrain it