$D^0 \rightarrow \mu\mu$

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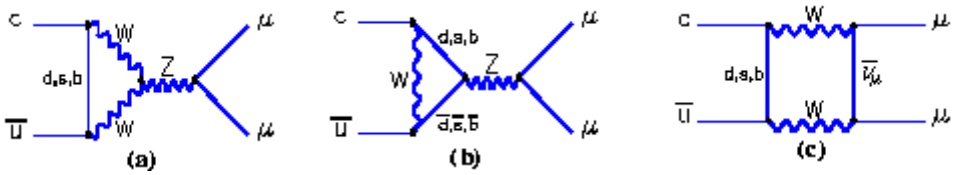
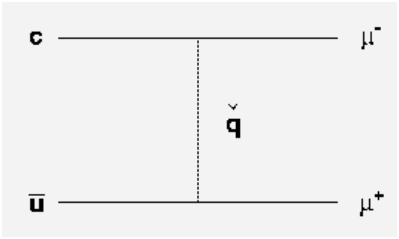
- $D0 \rightarrow \mu\mu$ is an FCNC decay, GIM suppressed in the Standard Model
  - ➥ **$B(D0 \rightarrow \mu\mu) \approx 3 \times 10^{-13}$ in SM,**



  - ➥ **but can be as large as 3.5×10^{-6} in some RPV SUSY models (squarks behave as leptoquarks).**

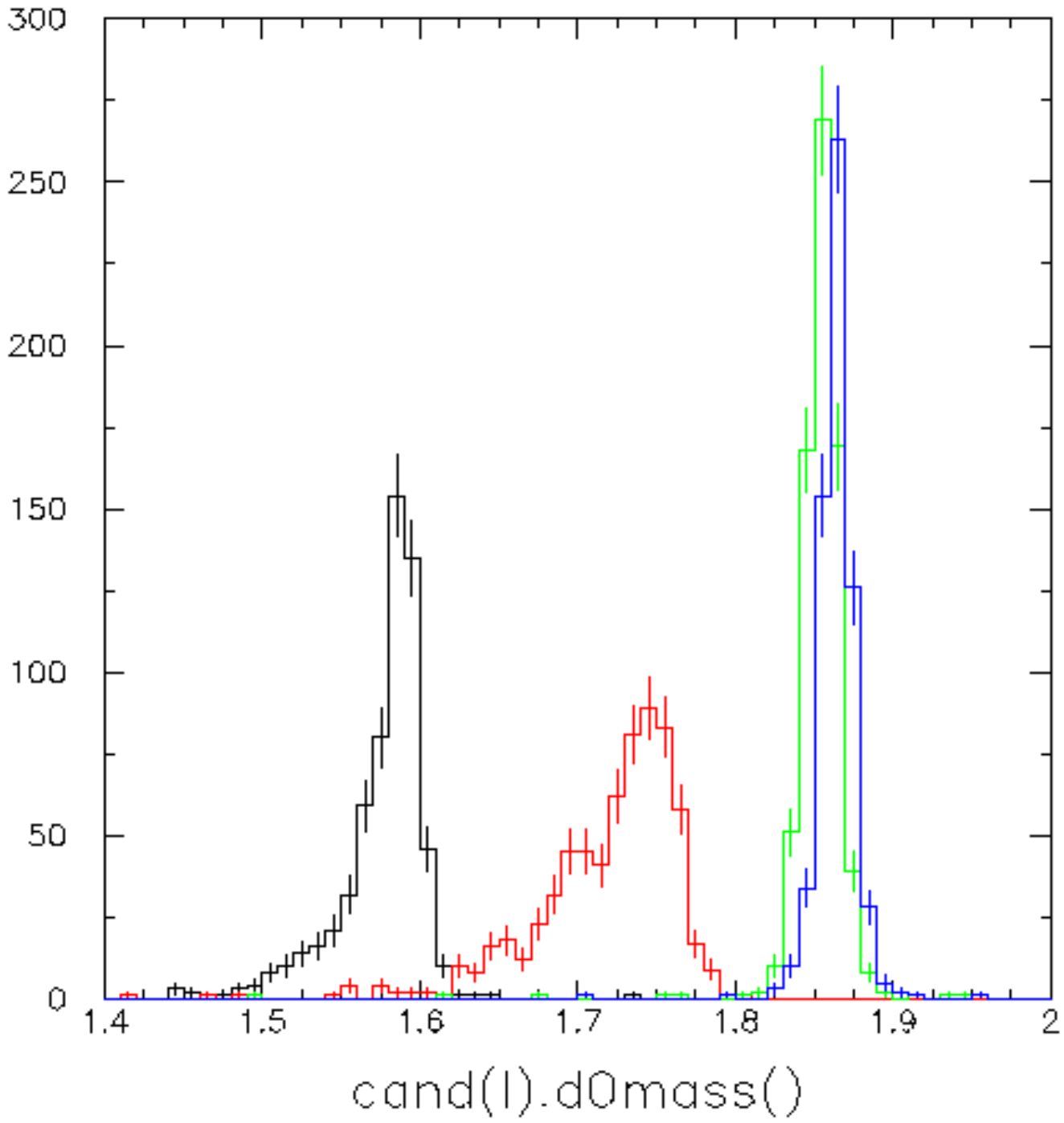


  - ➥ **Best limit (BEATRICE) is 4.1×10^{-6} @ 90% CL.**
  - ➥ **We think we can meet or surpass that with data in hand. (How well depends on BG level.)**
  - ➥ **See CDF note 6273**

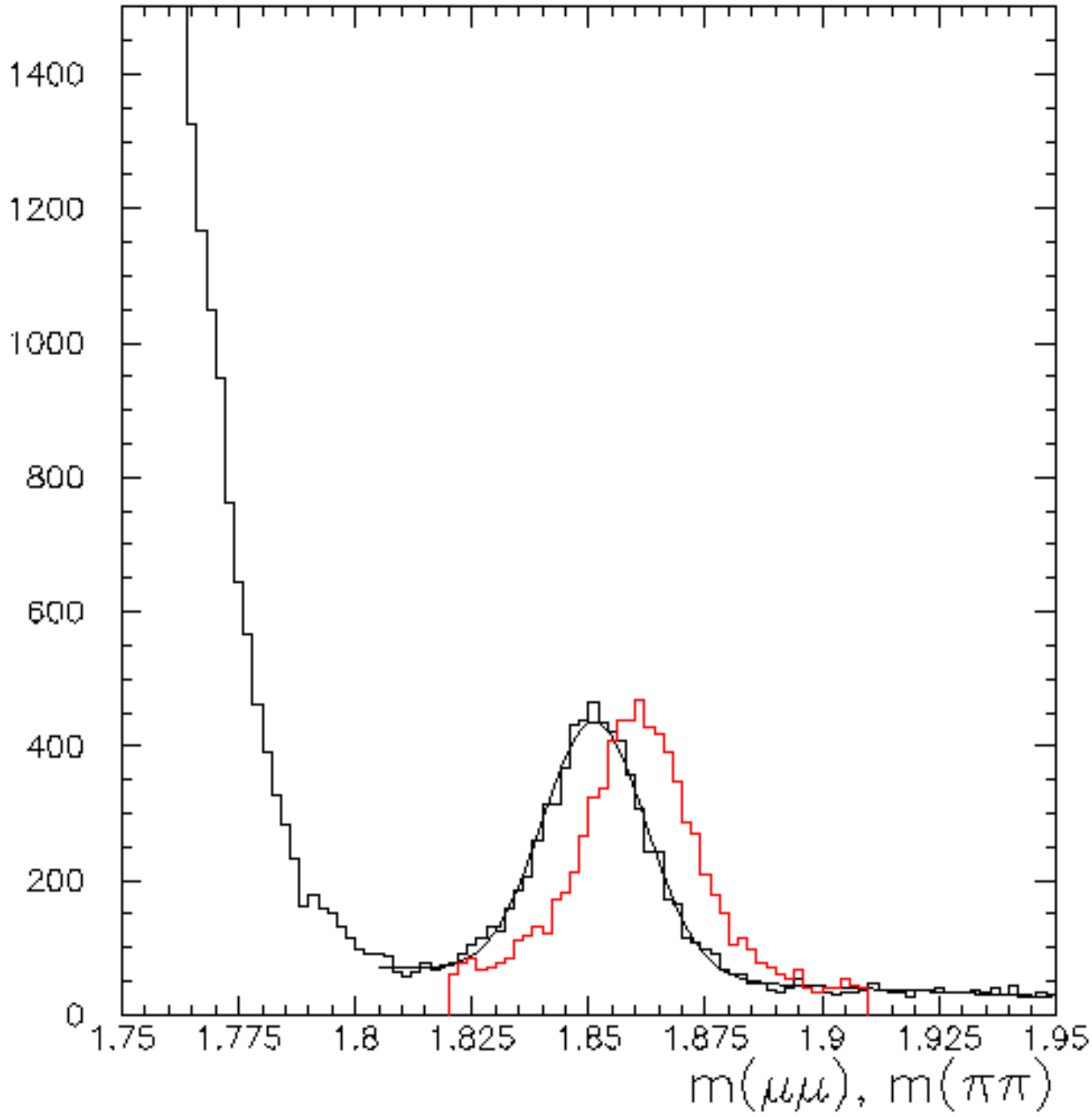
Analysis strategy

- Leverage huge SVT fully-reconstructed charm yields
  - D0 -> K pi ~ 6 nb
    - with D* tag ~ 2nb
  - D0 -> pi pi ~ 210 pb
    - with D* tag ~ 70 pb
- Use SVT-triggered D0 -> K pi, D0->pi pi samples to understand acceptance, backgrounds, signal normalization
  - D0->mu mu signal looks like D0->pi pi, with two muon tags, and about a 10 MeV (~1sigma) mass shift
  - Ideally, BG should be dominated by D0->pi pi (BR 1.4E-3), where both pions fake muons
  - ~1.4% pi->mu fake rate
    - BG should be equivalent to BR=3E-7
    - may be better if we use CMP, or at least use CMP at high momentum (we don't do that yet)
    - BG estimate currently much higher: BR ~ 2E-6
      - need to do much better before this could yield a credible discovery; but it should be possible

MC spectra (mumu mass)



Mass offset, K pi tail



Ingredients

- Number of reconstructed D0->pi pi with both tracks fiducial in CMU (for normalization)
  - ➥ **would improve x1.5 by using CMX**
- Muon ID efficiency
- Expected background
  - ➥ **doubly-mistagged D0->pi pi**
  - ➥ **combinatorial BG (a few real muons possible?)**
- Number of signal events, or an upper limit, based on observed number of events

$$B(D^0 \to \mu\mu) = B(D^0 \to \pi\pi) \times \frac{N(D^0 \to \mu\mu)}{N(D^0 \to \pi\pi)} \times \frac{\epsilon(D^0 \to \pi\pi)}{\epsilon(D^0 \to \mu\mu)},$$

or in the case of an upper limit,

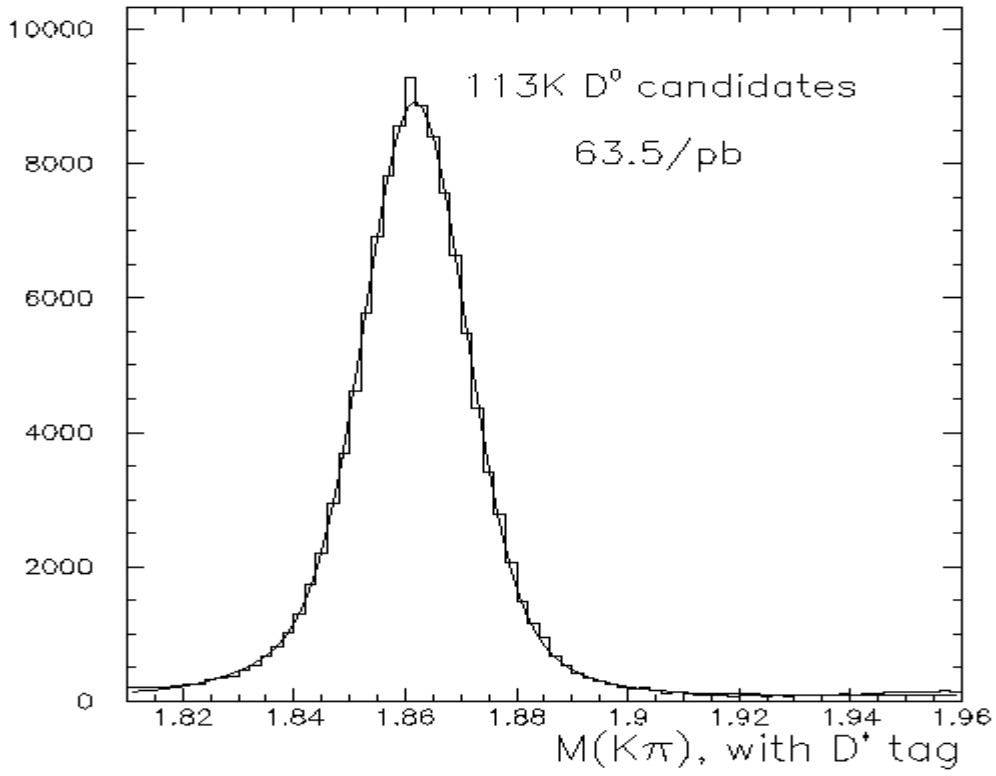
$$B_{90\%\mathrm{CL}}(D^0 \to \mu\mu) = B(D^0 \to \pi\pi) \times \frac{N^{\mathrm{upper}}_{90\%\mathrm{CL}}}{N(D^0 \to \pi\pi)} \times \frac{\epsilon(D^0 \to \pi\pi)}{\epsilon(D^0 \to \mu\mu)}.$$

Event selection

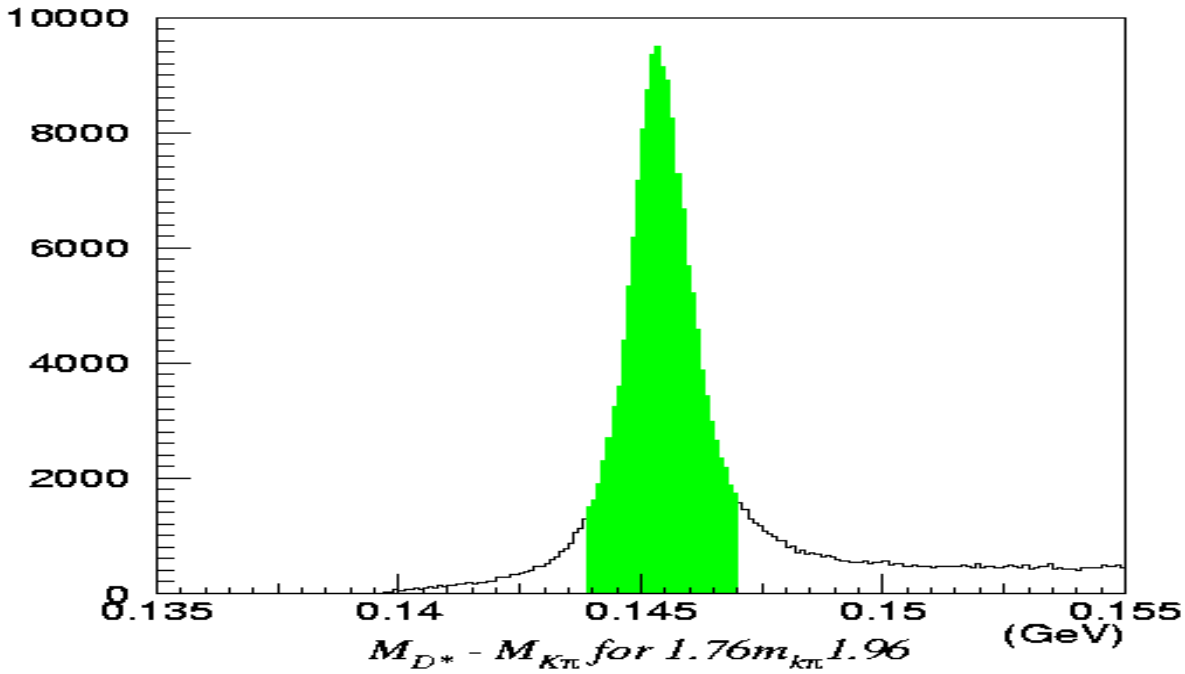
- Start with hbot0h on CAF1
  - **40M events, runs 138425-156116, good runs ~63.5 pb^{-1}**
- defTracks (pT>0.3), numCTHitsAx ≥25, numCTHitsSt≥25
- COT→XFT→SVT match (>5sigma window)
- d*d<0, q*q<0
  - **No use of offline impact parameters, except in computation of track momenta at intersection!**
- Use CTVMFT to calculate intersection, momenta (no $\chi 2$ cut)
- 1.5 < m(μμ) < 2.05 GeV (use μ hypothesis)
- ⇒ selects 8.6% of hbot0h, write binary microDST
- Add bachelor pion (use CTVMFT to get momenta)
  - **no XFT/SVT match, Δm < 0.17 GeV**

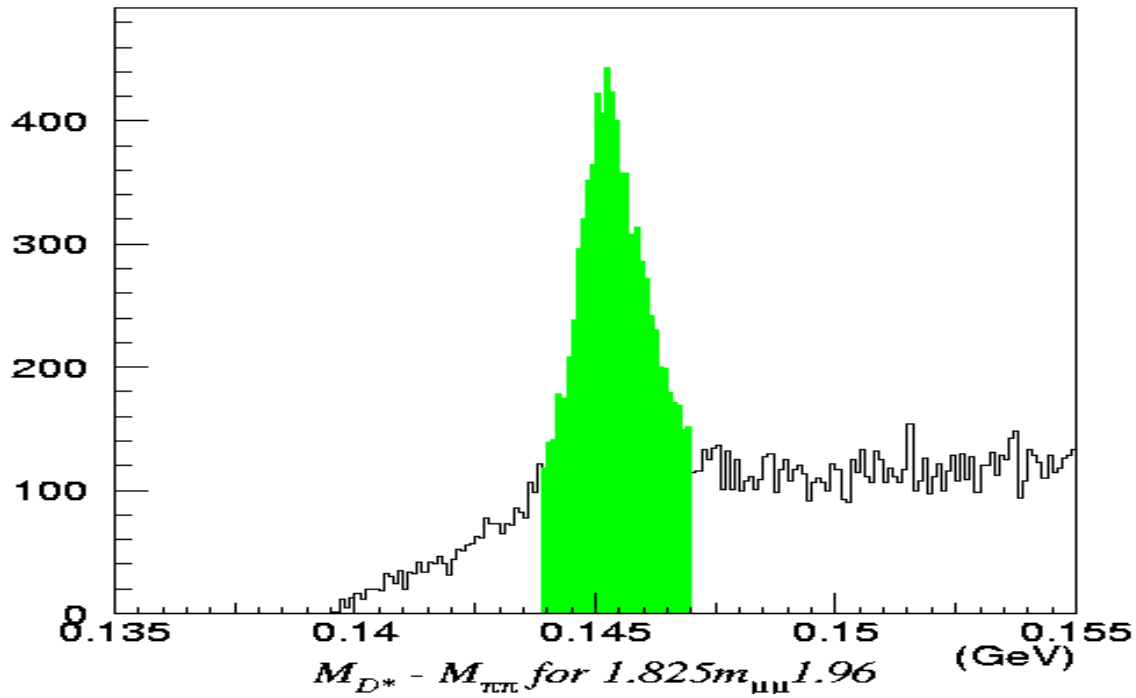
Event selection

- Tighten Δm cut: 0.144 < Δm < 0.147 GeV
- At this stage, D*-tagged D0->Kpi yield is
  - **140K candidates, before good run list**
- Require track pT>2, 120um<=dSVT<=1000um, at least 3 SVXII layers used on each D0 track, 2degrees<dphi<90degrees, Lxy>0
  - **137K candidates, before good run list**
- After good run list (63.5/pb)
  - **113K D0->Kpi candidates with D* tag**



D*: 0.144<dm<0.147



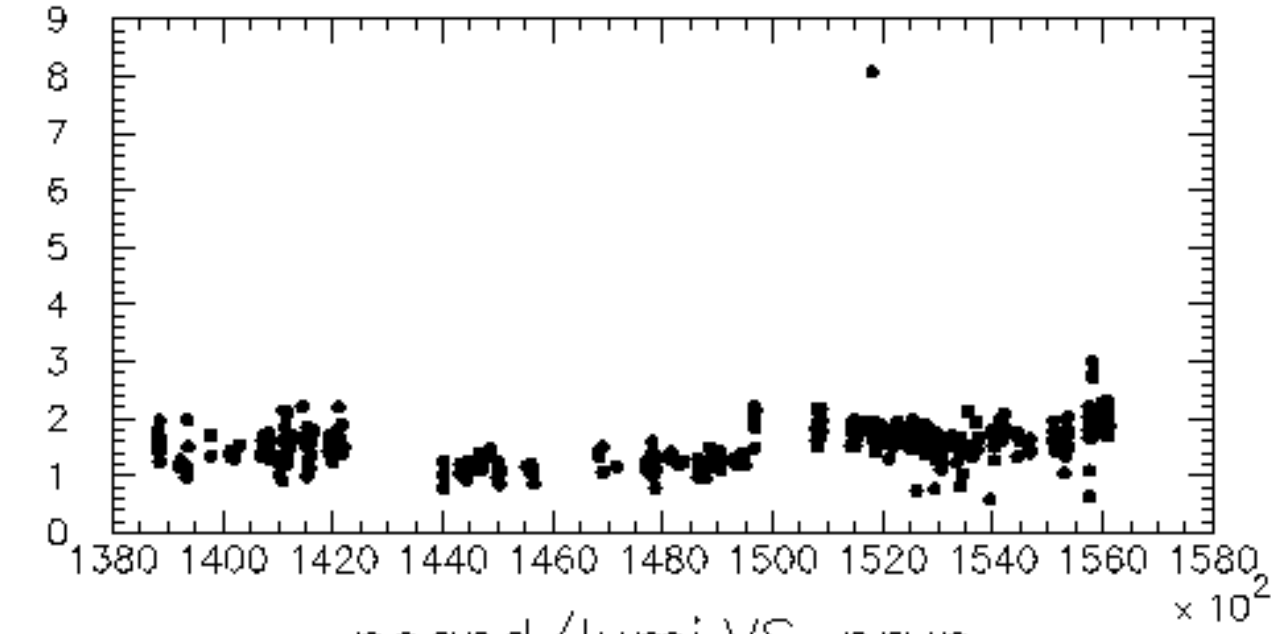


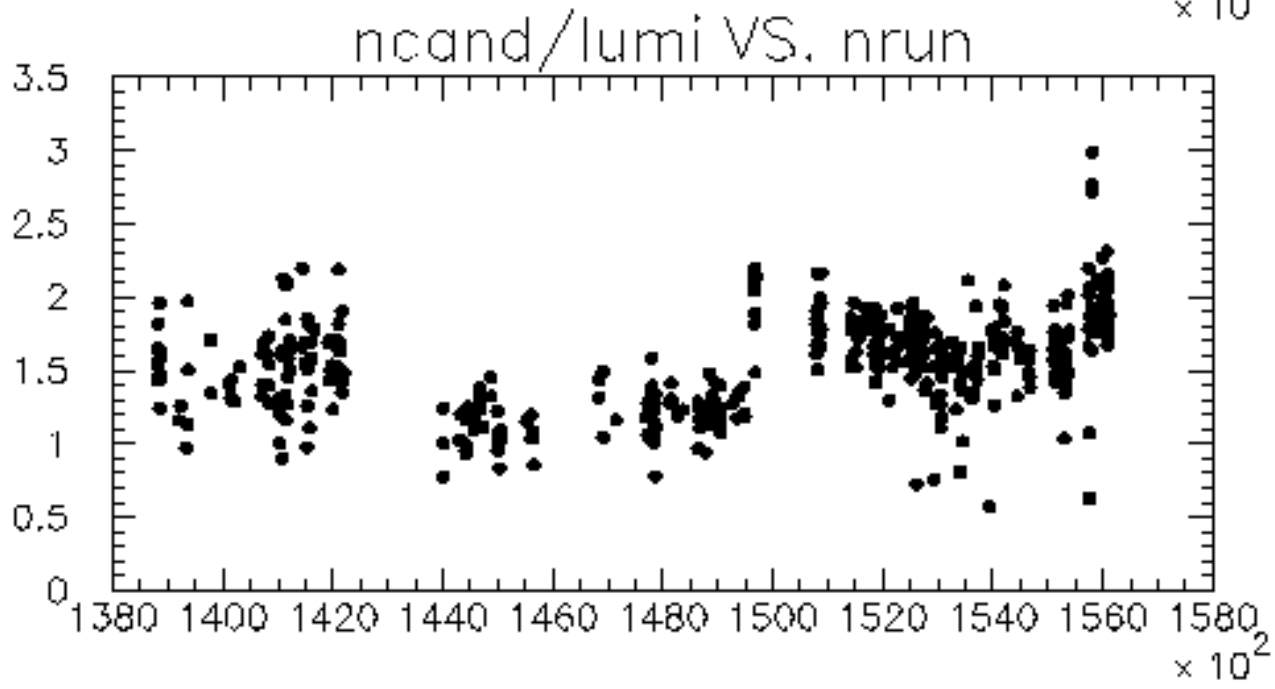
Good run list

- 138425<=runnumber<=156116
- "status" flags == 1:
  - runcontrol, shiftcrew, clc, svx, svt, l1t, l2t, l3t, offline
- "offline" flags == 1:
  - cot, cmu
- 440 runs, 63.55/pb
  - we have at least one D*-tagged D0->Kpi in our ntuple for each of these runs

- Check: relax svx, svt status; require runnumber<=152625 (typo in note)
  - confirm CDF 6288: 458 runs, 39.096/pb

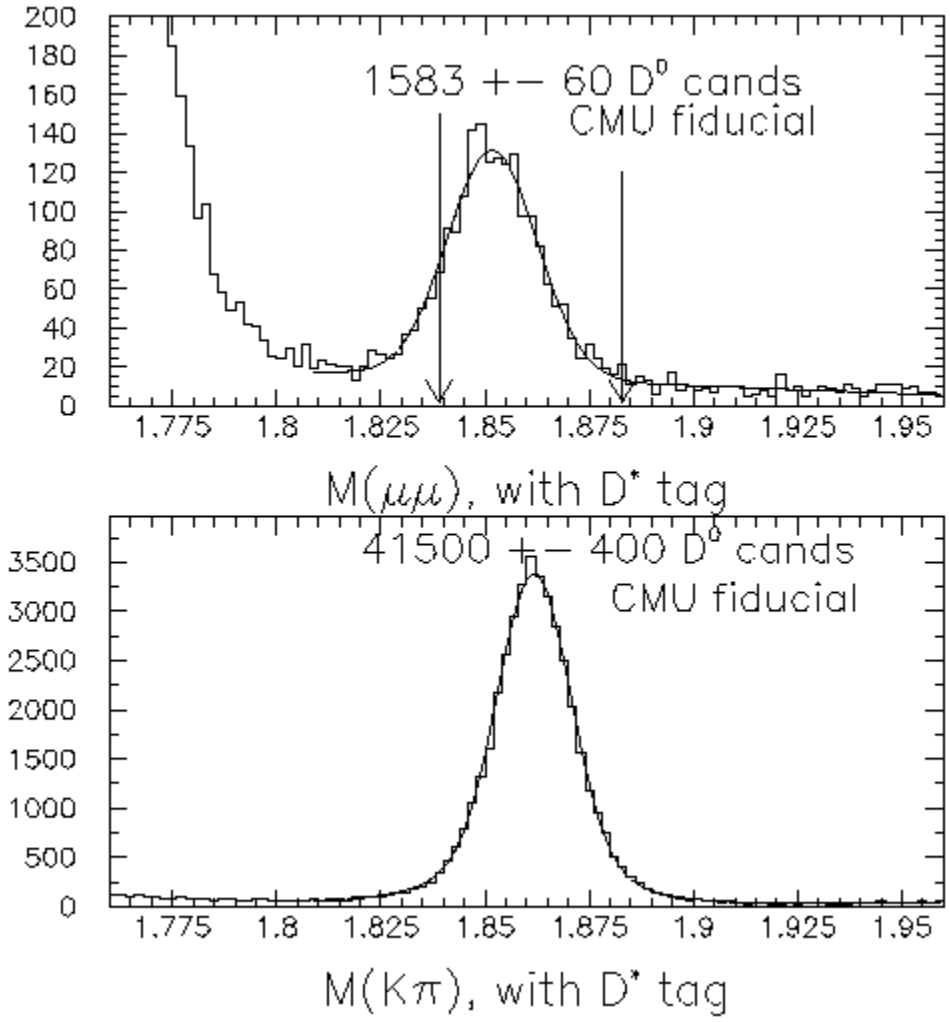
Check effective D* xsec vs run





Normalization signal

- See 4345+-90 D*-tagged D0->pi pi
  - 1583+-60 after CMU fiducial cuts (x0.36)
  - M(pipi) peak at 1.861, sigma=11MeV
  - M(mumu) peak at 1.851, sigma=11MeV



Relative efficiency

- pipi is kinematically ≈ identical to $D^0 \to \mu\mu$
  - ➥ **acceptance effects cancel**
  - ➥ **need relative $\mu\mu/\pi\pi$ efficiency**
  - ➥ **we steal it from other authors for now**

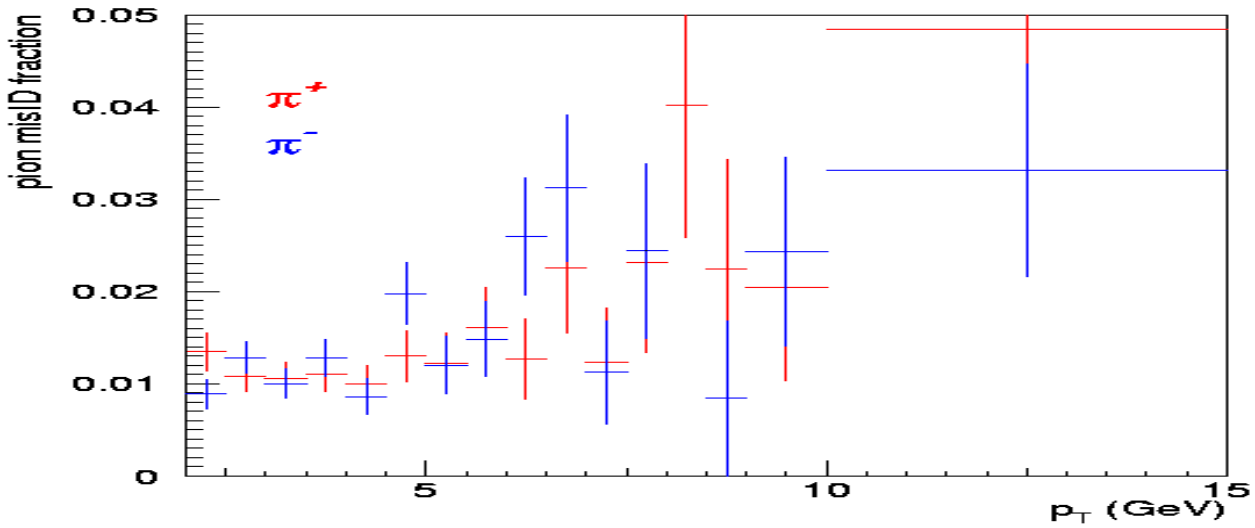
- CDF 6029 quotes 97±1% μ stub efficiency after `isFiducial()` requirement
  - ➥ **We can check later using μ+SVT sample**
  - ➥ **loophole: muons too close in CMU**
    - ➥ avoid by requiring ~4.5 drift cell separation in CMU

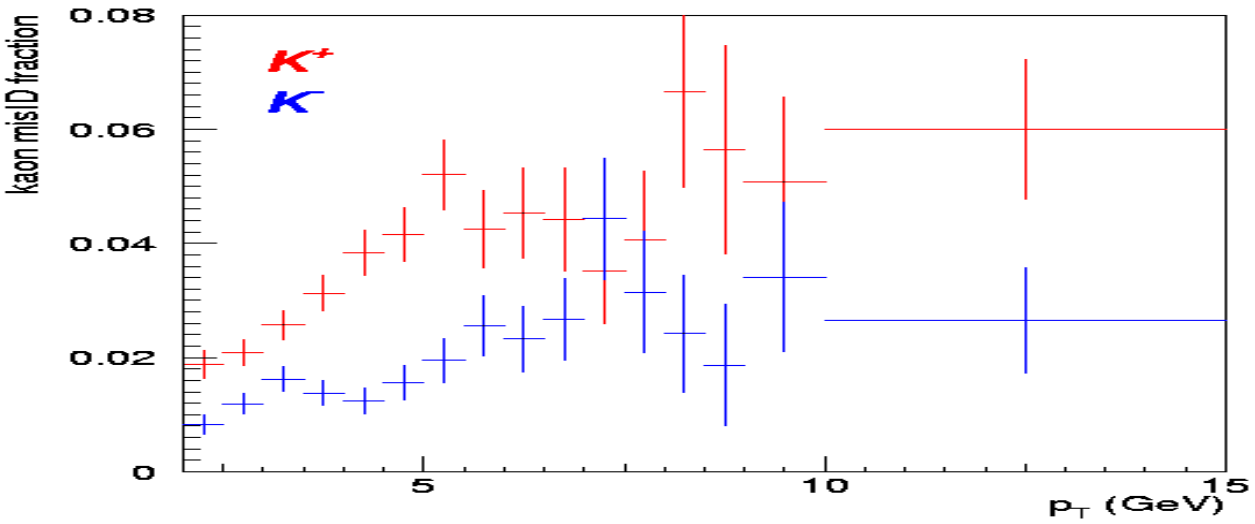
- CDF 6114 finds `chsqXPosition<9` (a.k.a. `MOXFTM`) to be >98% efficient over entire 2-10 GeV range relevant to us

- CDF 6018 finds a 4.5±0.2% π reco inefficiency due to decays-in-flight and hadronic interactions

- We inflate the errors and take $\varepsilon(\mu\mu)/\varepsilon(\pi\pi)$ to be 1.012±0.045

K->mu, pi->mu BG





- Avg Pi->mu fake rate is ~1.4% (~2.4% for K->mu)
- Thus, expect (naively) 1583*0.84*0.014**2=0.3 BG events
  - ➥ **0.84 comes from 1 sigma shift of 2 sigma window**

BG handles

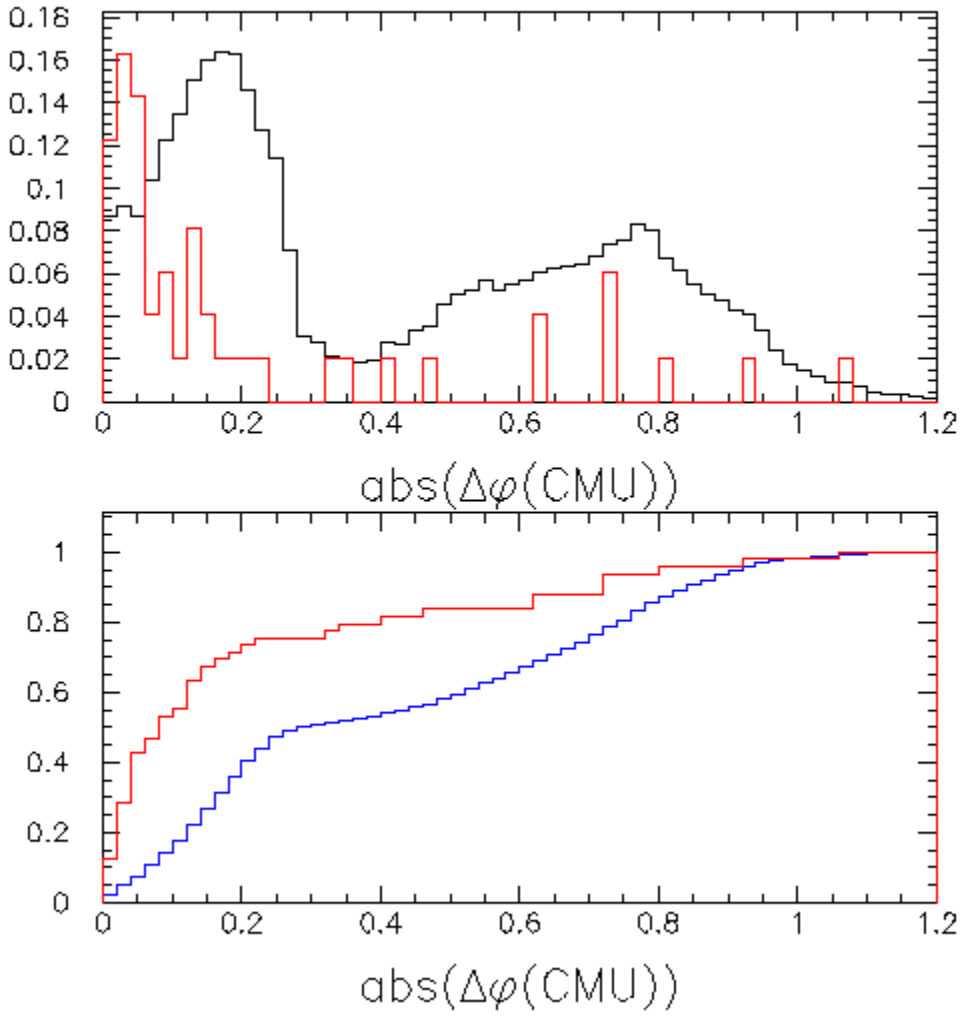
- Resonant BG:
  - look at double-tagged Kpi events
  - look at single-tagged pipi events
- Combinatorial BG:
  - look at high-mass pipi with 1 muon tag
  - look at high-mass pipi with 2 muon tags
- Having two handles on each allows us to use one for tuning the cuts and another for estimating the remaining BG

First realistic BG estimate

- Ignoring sideband subtraction …
- 39791 Kpi events 1.840-1.885 GeV
  - **1494 have 1 muon tag (2p(1-p))**
  - **49 have 2 muon tags (p**2 ?)**
- Naively expect (0.024+0.014)*39791=1512 (OK)
- Expect 0.024*0.014*39791=13 (oops, see 49)
  - **factor of 3.8+-1.1**
- Now look at single-tagged pipi peak
  - **crude sideband subtraction-> 38+-10 / 1583 / 2**
    - 1.2+-0.3%, consistent with ~1.4%
- High-mass pipi sideband (1.90-2.05 GeV)
  - **558 events before muon ID**
  - **47 have 1 tag (47/558/2 = 4.2%) (real muons?)**
  - **7 have 2 tags (0.042**2*558=1, oops)**
- 3.8*0.3 + 7x44/150 = 3.2 total BG (oops)

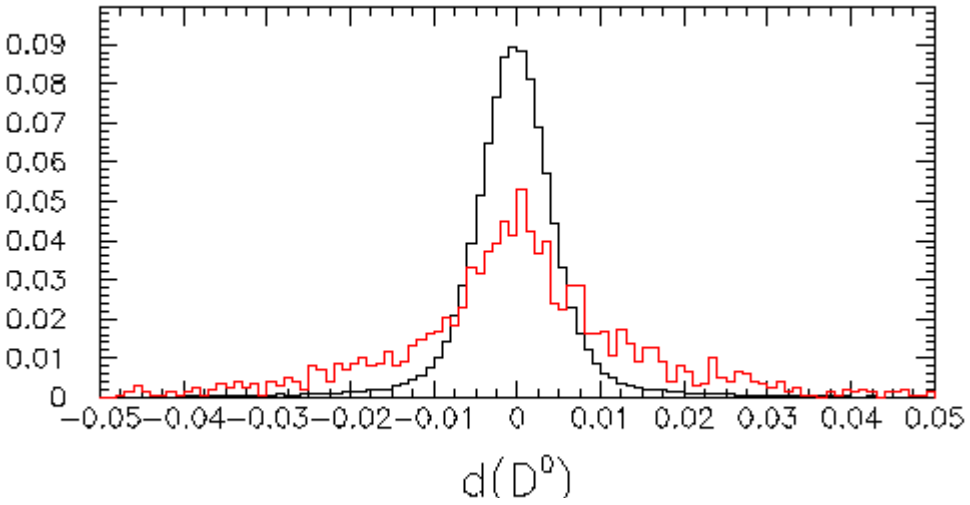
What is to be done?

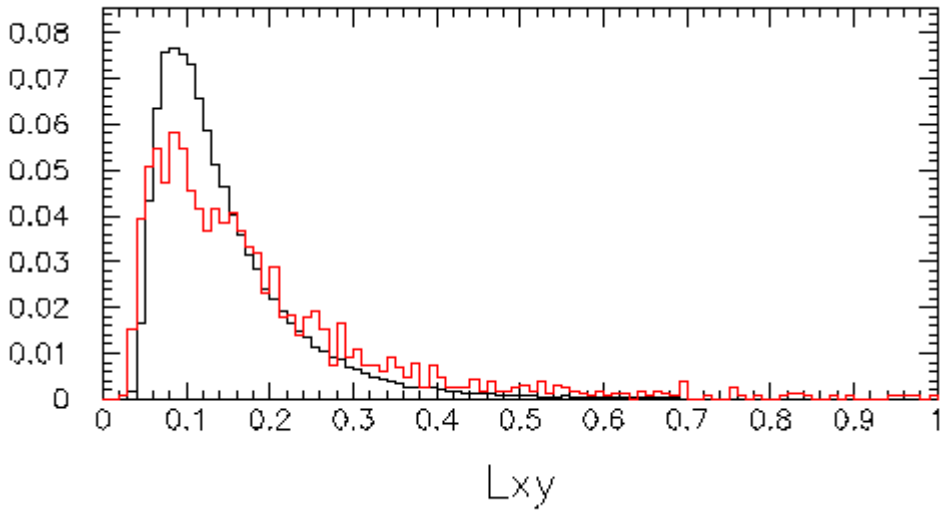
- Hand-scan of double-tagged Kpi events reveals many cases in which 2 D0 daughters extrapolate very close together in CMU
  - **we swim tracks (crudely) to CMU, check dphi**
  - **~half of 2-tag, only 10-15% of 0-tag, have dphi<100mrad at r=347cm**



Beating down the BG, episode 2

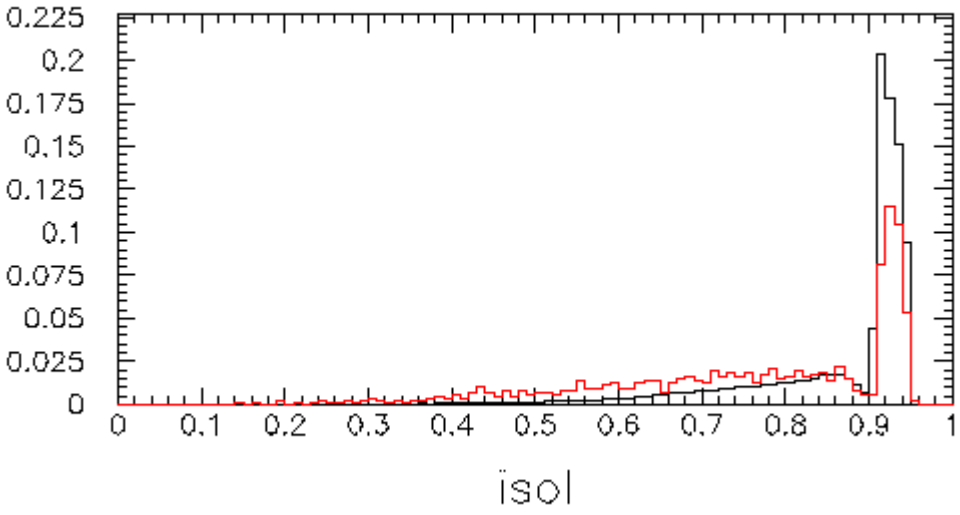
- Combinatorial BG should be less likely to point back at beamline than (primary) D0. Also, D0 from B decay may have real muons nearby.
- Maybe also more displaced (Lxy)?





Other cuts?

- Maybe B decay and gluon splitting to ccbar can produce nearby leptons, and also other nearby tracks?
- Try pt(D0) / sumpt(cone of 0.25)
- This is Kpi signal vs pipi high-mass sideband



- Maybe require CMP stub if a track is CMP fiducial and of sufficient momentum to reach CMP?
- Maybe cut on CMU slope match (thanks TJL)?
- NB (Luciano): another source of "correlation" is variance in tag rate: <x**2> = <x>**2 + var(x)
  - ➥ **pT dependence causes largest variance?**

Backgrounds & cut optimization

- Giovanni Punzi derives figure of merit $S/(1.5+\sqrt{B})$
  - Makes sense: ~S for small B, ~$S/\sqrt{B}$ for large B
  - Can use $S \propto N\pi\pi$
  - Need to estimate B = expected BG
    - for optimization, we use double-tagged Kpi for resonant BG and single-tagged high-mass pipi sideband for combinatorial BG
  - Interesting: isolation cut reduces BG but does not improve FOM (before good run list, it marginally improved FOM)
    - Optimal cuts depend on exposure

Cut	S	$\pi\pi$	comb	BG	FOM
`.true.`	1586	1.28	1.06	2.33	524
$\lvert d_{xy}\rvert < 0.0150$ cm	1534	1.15	0.80	1.95	529
$\lvert\Delta\phi_{\rm CMU}\rvert > 0.085$	1452	0.63	0.77	1.40	542
$L_{xy} < 0.45$ cm	1573	1.05	1.02	2.07	535
all but L_{xy}	1401	0.60	0.49	1.09	550
all but $\lvert\Delta\phi_{\rm CMU}\rvert$	1536	1.00	0.73	1.73	545
all but d_{xy}	1446	0.55	0.77	1.32	546
all	1409	0.53	0.47	0.99	564

Table 2: Cut optimization results.

The BG strikes back?

- After tuning, we check double-tagged high-mass sideband to estimate combinatorial BG and single-tagged pipi to estimate resonant BG

- See 5 double-tagged events in 1.90-2.05 GeV window. Scale down by 44MeV/150MeV
  - **1.5+-0.7 events (combinatorial)**

- See 1429+-56 untagged pipi events after all cuts, 22+-8 with a single muon tag
  - **divide by 2 (2p(1-p)), x0.014 fake rate, scale up x2 (observe 21 double-tagged Kpi, expect 12)**
  - **get 0.3+-0.1 expected resonant BG**

- So total estimated BG is 1.8+-0.7 events
  - **a bit disappointing, but still an improvement**
  - **combinatorial BG estimate is based on very low statistics, could be a fluctuation**
  - **should we look harder before we open the box?**

Final sensitivity (closed box)

- Fit 1429+-56 events in normalization mode
- Scale by 0.95 for 2sigma mass window
- Scale by 1.012+-0.045 for mumu/pipi efficiency
  - ➥ **yields 1374+-82 events**

- So-called single-event sensitivity is
  - ➥ **1.4E-3 / 1374 = 1.0E-6**

- If no event is found, 90%CL limit will be (ignoring systematics)
  - ➥ **1.4E-3 * 2.3 / 1374 = 2.3E-6**

- But we expect 2 events, so we would get
  - ➥ **1.4E-3 * 5.3 / 1374 = 5.4E-6**

- Bummer?
  - ➥ **Before looking at the signal region, we should be confident in the cut optimization and the figure of merit. Also should decide a priori how to update cuts for coming months' data.**

What's next?

- More checks possible:
  - Ran on hadronic sample with J/psi mass window; can check some muon ID stuff
  - Attempting to get CMU slope info, to see if a cut significantly reduces muon misID
  - Can use "official" CMU extrapolation, probably get a cleaner separation for dphi(CMU)

- Next week:
  - Want to bless some P.R. plots so that Ivan can show our search potential at LaThuile

- Future directions:
  - Let more data roll in, hopefully reach a few E-7
  - Rob wants to do $\pi\mu\mu$
  - Bill wants to do $e\mu$, ee