OBSERVATION OF THE RARE CHARMED B DECAY,

$$B_d^0 \rightarrow D^{(*)+} a_0^-$$

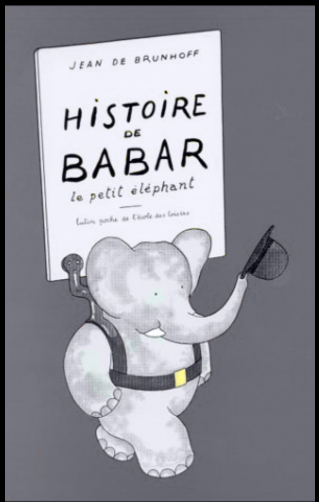
AT THE BABAR EXPERIMENT

ON FINDING A NEEDLE IN A HAYSTACK

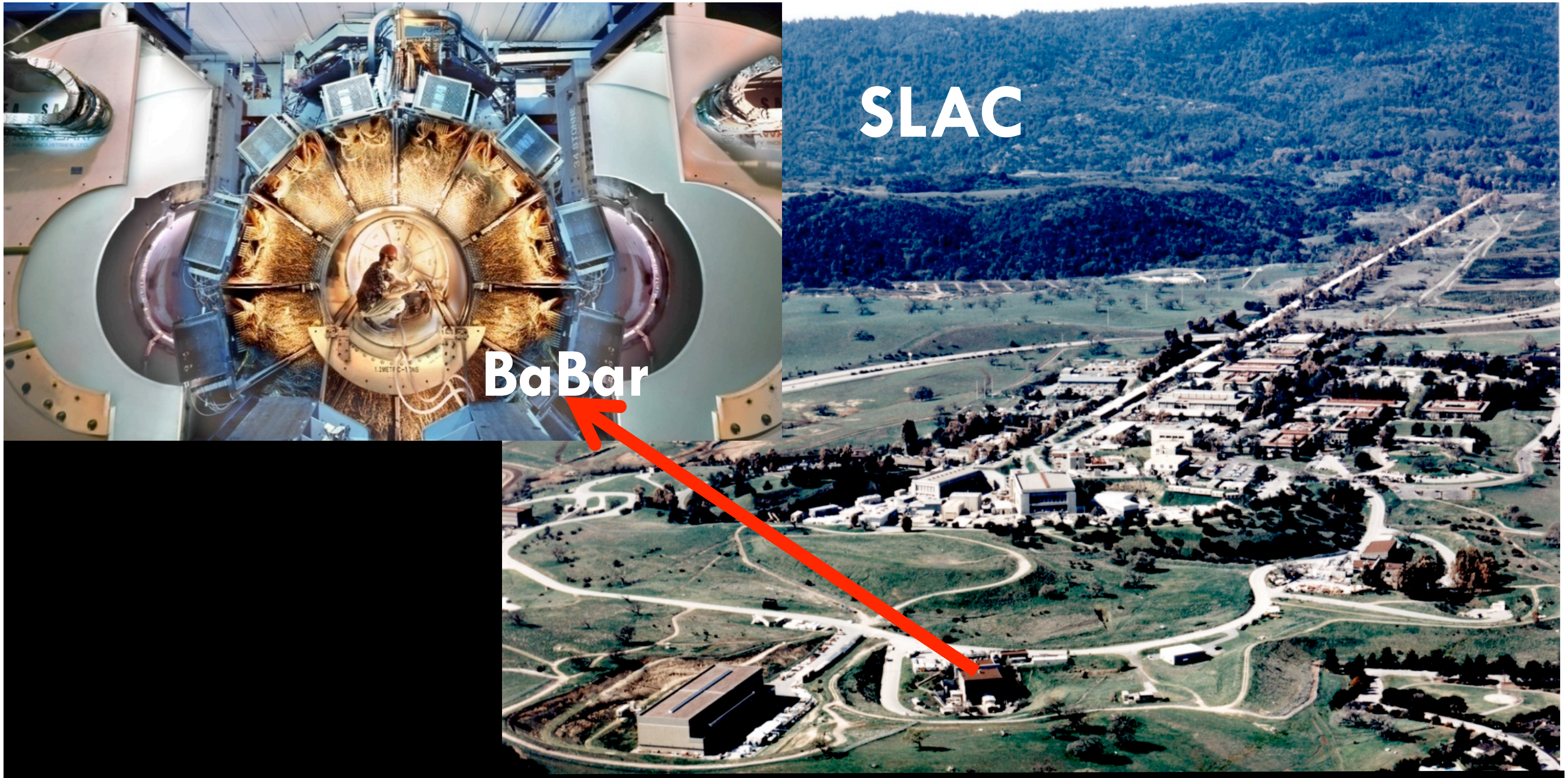
Hella Snoek - Nikhef

Virginia University HEP seminar

Contents



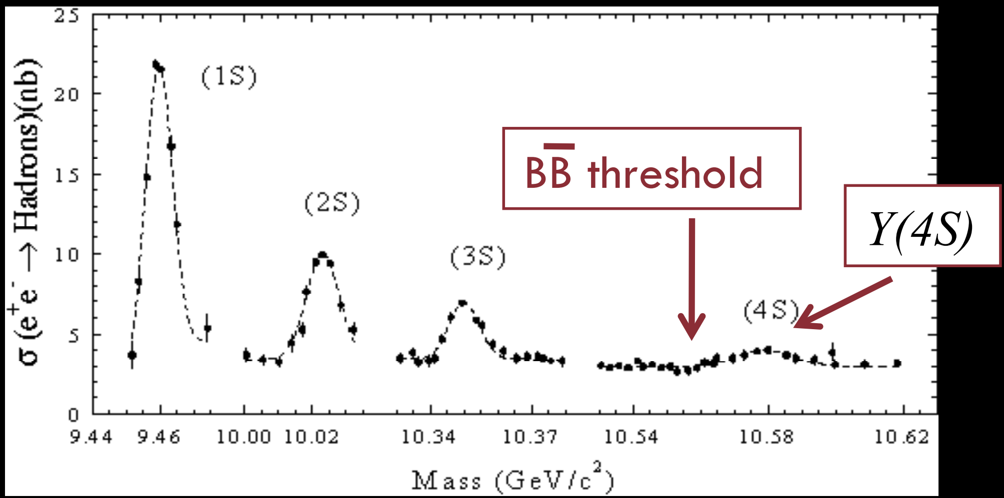
- BaBar and CP violation
- Physics goals and production mechanism
- Analysis
  - Optimization of signal selection
  - Setup of three dimensional likelihood fit
  - Results
- Interpretation and outlook


SLAC
BaBar

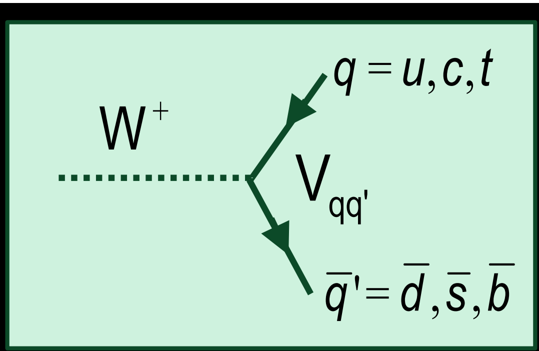

PEPII's LINAC is1.9 miles long: longest building in the world!!

BABAR and anti-matter

- BaBar at PEPII collider, SLAC ('99-'08)
- Focus on measurements of CP violation: differences between matter/anti-matter
- Run at e^+e^- collisions at $\Upsilon(4S)$: clean coherent B-meson production
- (On tape 526.5 million $B\bar{B}$ pairs)



CP violation in electroweak decays (1)



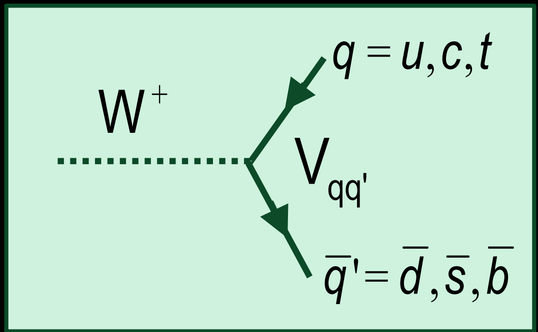
Quark changes flavor
due to weak interaction

$$\begin{array}{c} \\ u \\ c \\ t \end{array} \begin{array}{c} \begin{array}{ccc} d & s & b \end{array} \\ \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \end{array}$$

3x3 flavor changing currents

Cabibbo-Kobayashi-Maskawa
(CKM) matrix

CP violation in electroweak decays (1)



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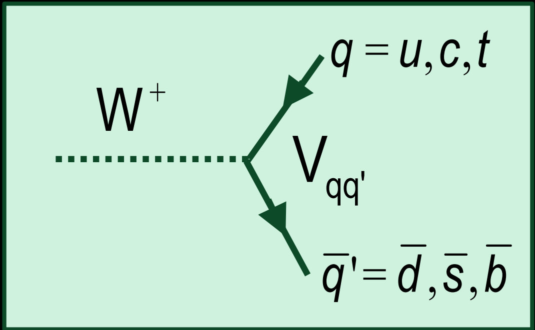
Cabibbo-Kobayashi-Maskawa (CKM) matrix

CKM Matrix must be unitary (conservation of probability):

- 9 equations (6 triangles)
- 4 free parameters, (3 magnitudes + 1 complex phase)

CP violation in electroweak decays (1)



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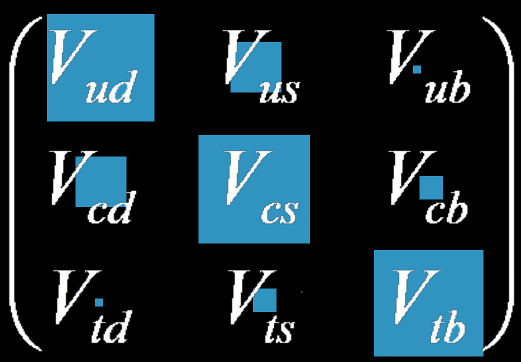
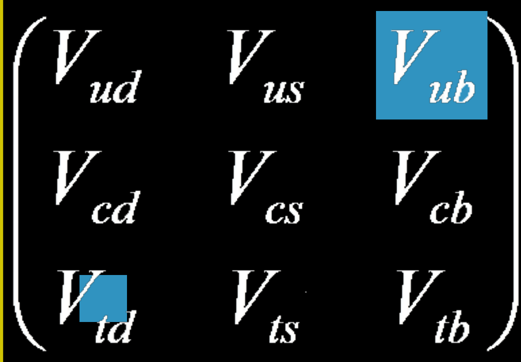
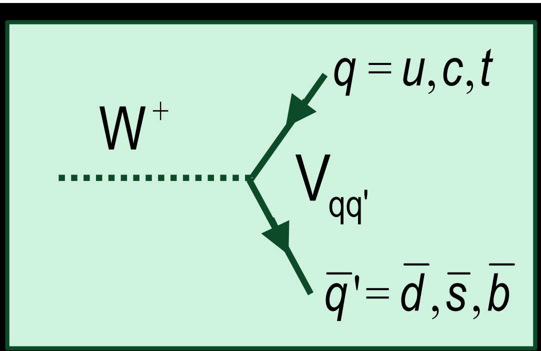


relative magnitudes



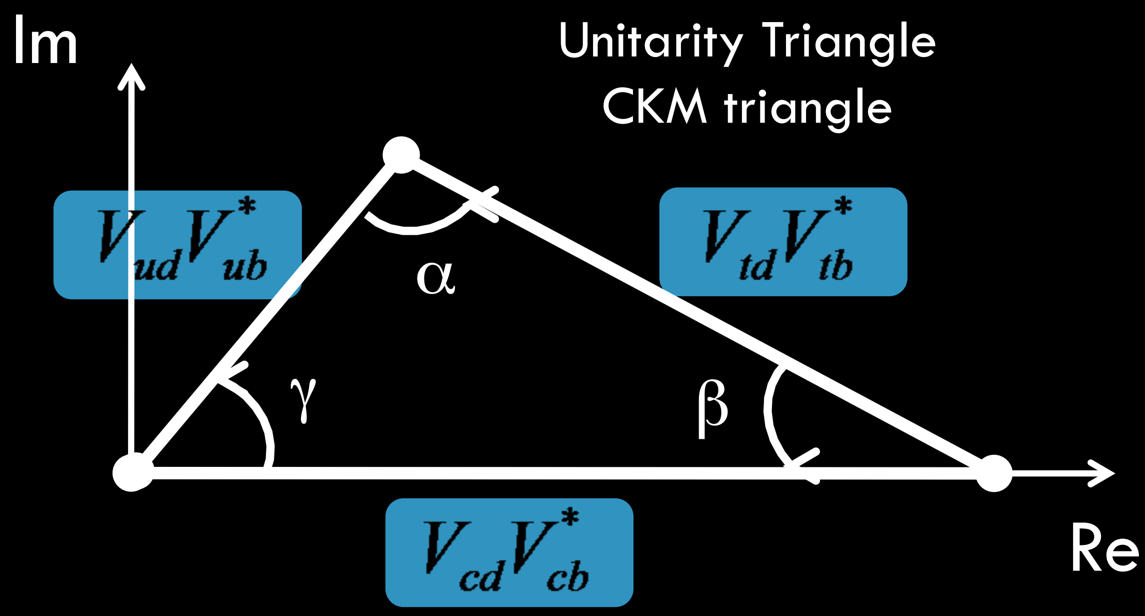
relative phases

CP violation in electroweak decays (2)



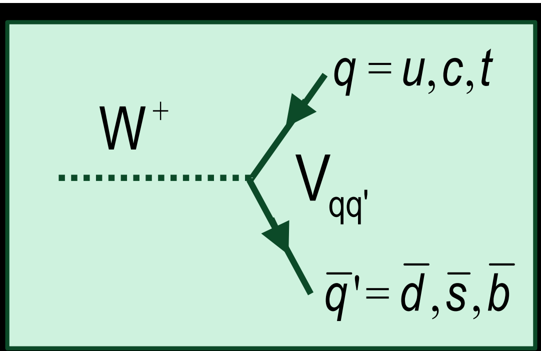
$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

Cabibbo-Kobayashi-Maskawa (CKM) matrix



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

CP violation in electroweak decays (2)



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

Cabibbo-Kobayashi-Maskawa (CKM) matrix

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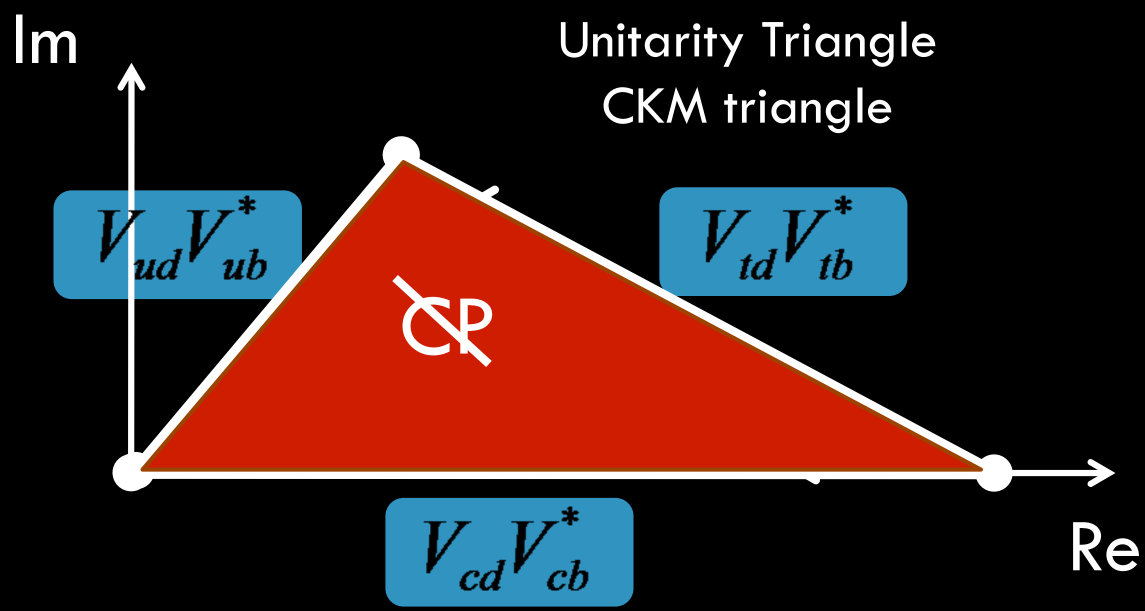
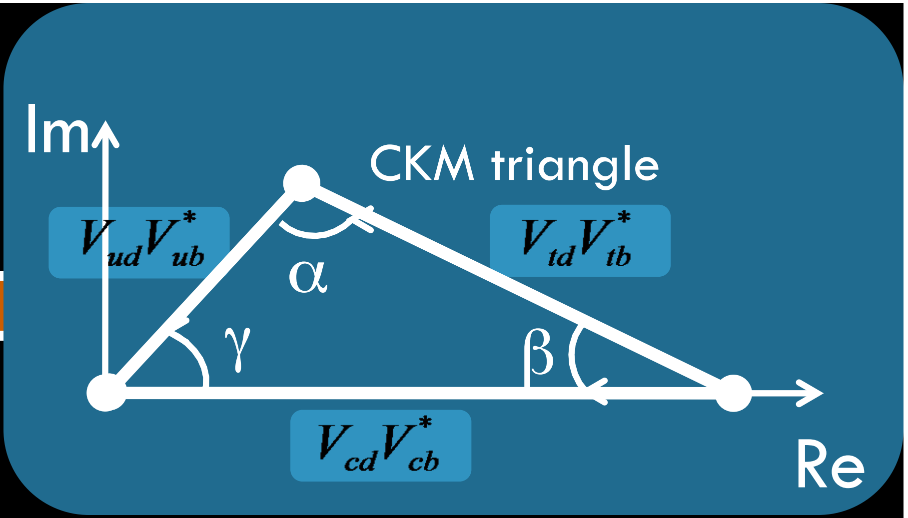
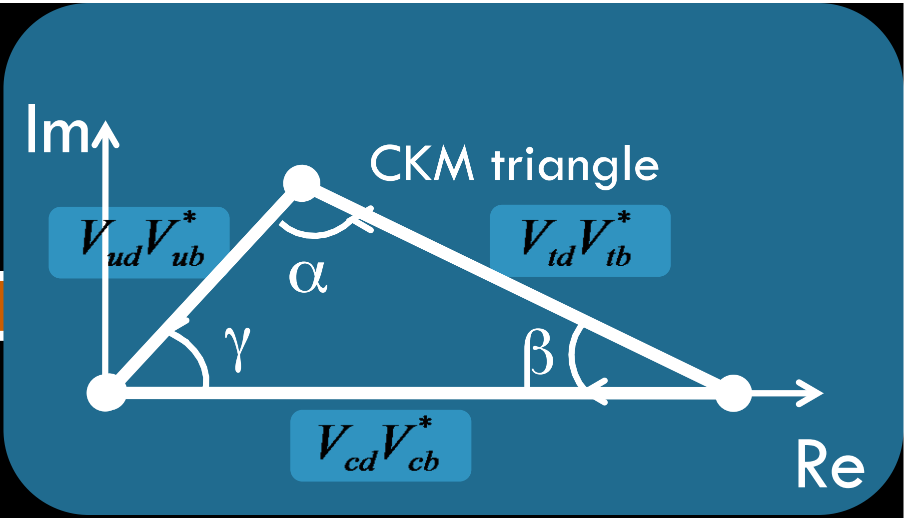


CKM angles



- Over-constraining CKM triangle powerful test of Standard Model

CKM angles



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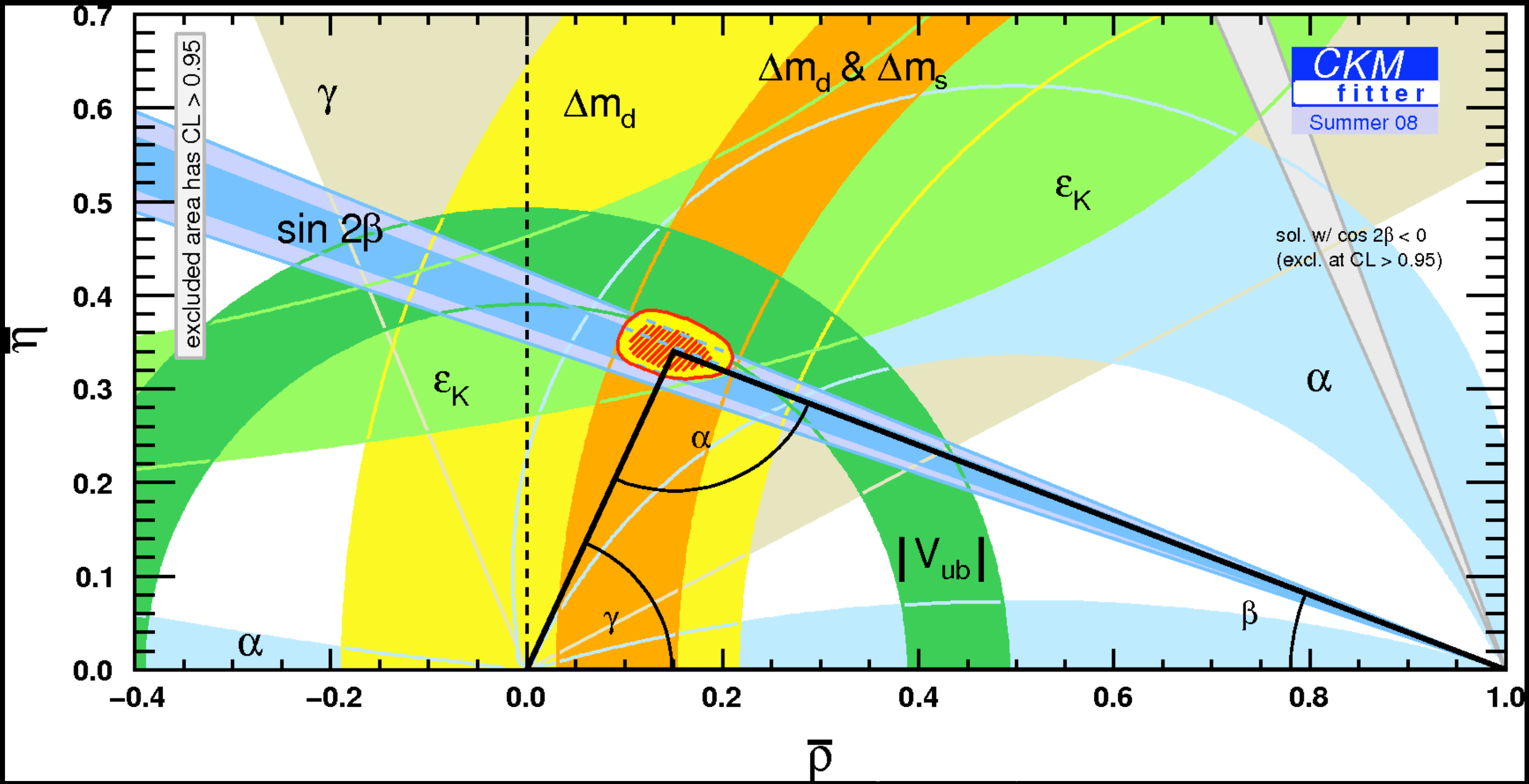

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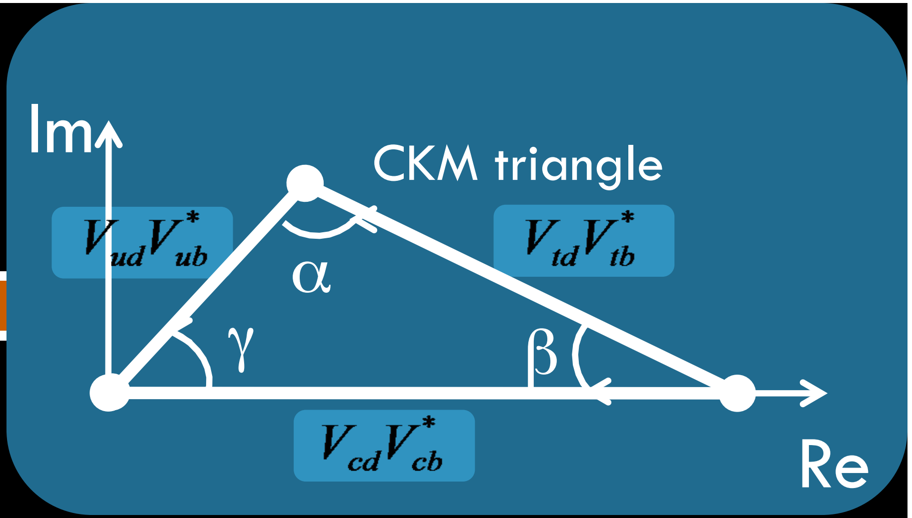
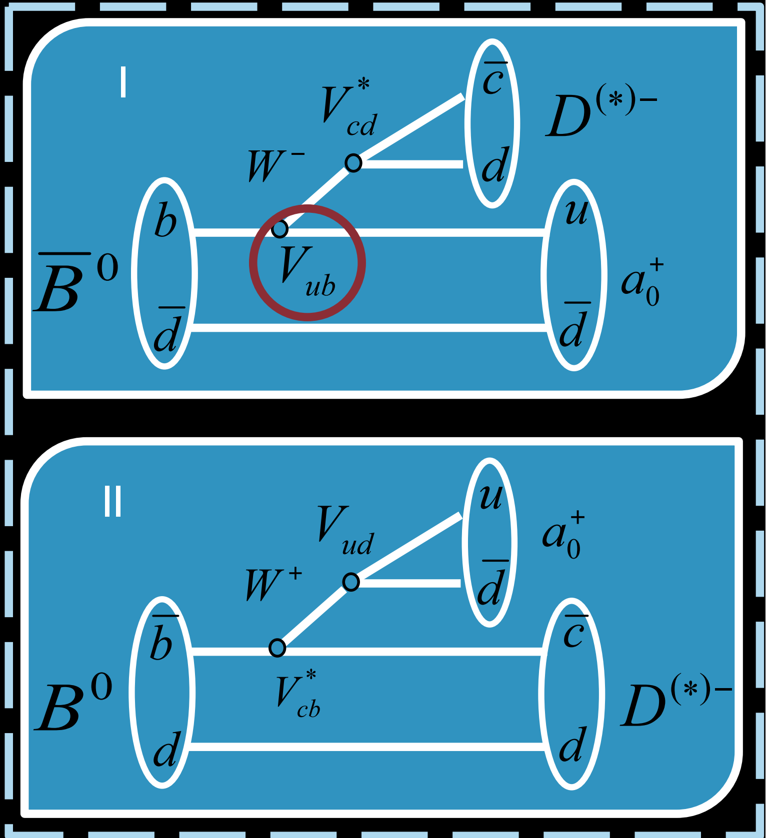


- Over-constraining CKM triangle powerful test of Standard Model
- CKM angle γ least constrained by measurements $\alpha = 88 \pm 5^o, \beta = 22 \pm 5^o, \gamma = 77 \pm 30^o$
  - Measured through time dependent interference in B decays
  - Current measurements through $B^0 \rightarrow D^{*+}\pi^-$ and $B^0 \rightarrow D^{*+}\rho^-$
  - $B^0 \rightarrow D^{*+}a_0^-$ could be more sensitive

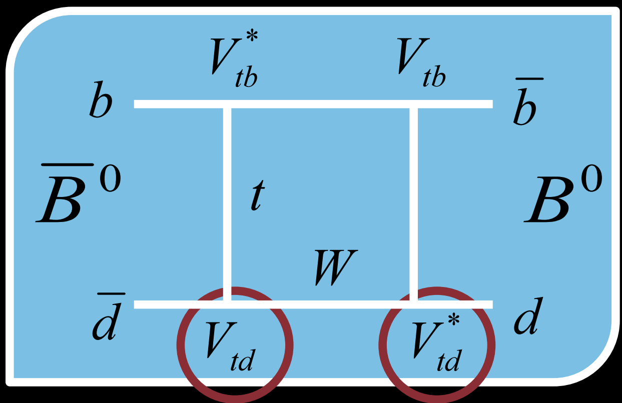
Sensitivity to CKM angle γ

- Same initial and final state.
- Weak phase difference gives $sin(2\beta+\gamma)$.
- Asymmetry amplitude to phase given by the amplitude ratio.



CKM angle γ

Oscillation process where anti B meson changes in B meson



CKM angle 2β

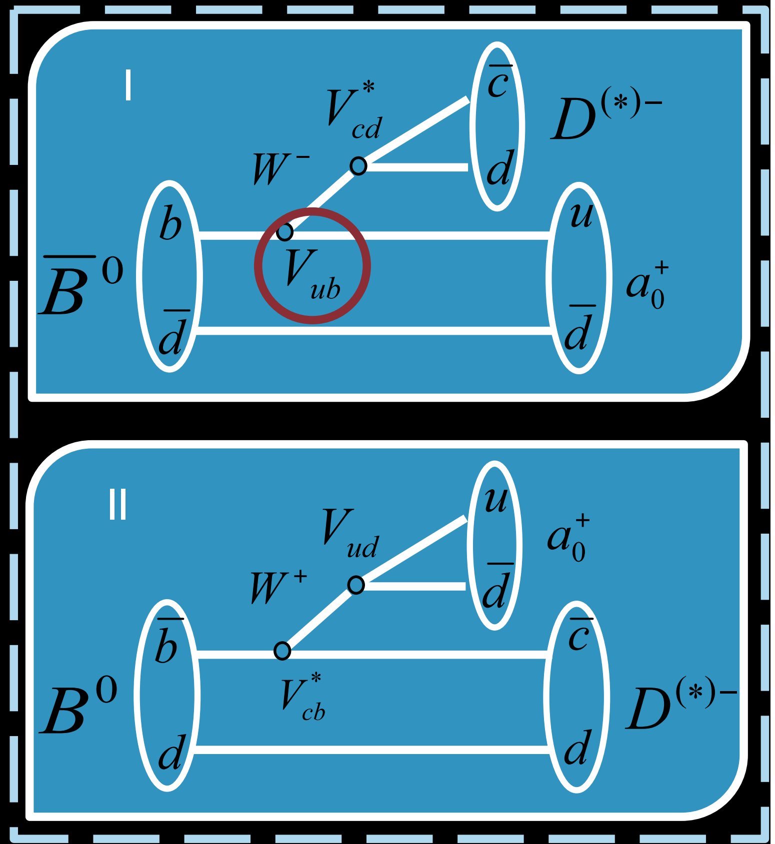
Sensitivity to CKM angle γ

- Same initial and final state.
- Weak phase difference gives *sin(2β+γ)*.
- Asymmetry amplitude to phase given by the amplitude ratio.

$$\text{Asym. amp.} \sim \frac{A_I}{A_{II}} \propto \underbrace{\left|\frac{V_{ub}^{*}V_{cd}}{V_{cb}V_{ud}^{*}}\right|}_{\sim 0.04} \times \underbrace{\frac{F_{B\to a_0}}{F_{B\to D}}}_{\sim 1} \times \underbrace{\frac{f_D}{f_{a_0}}}_{\sim 200}$$

Weak decay constants (MeV):

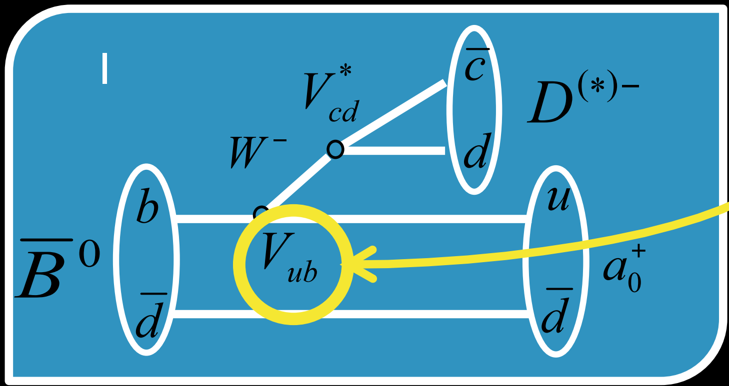
D^+	D^{*+}	π^+	ρ^+	a_0^+
200	300	130	200	1.1

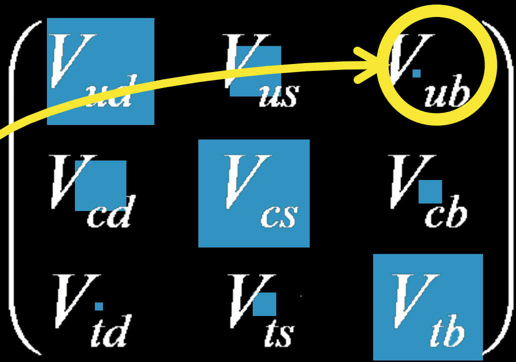


CKM angle γ

Asymmetry amplitude to CKM phase is large for $B^0 \to D^{*+} a_0^-$!
However, we also have *less events* because of low branching ratio.

So how large is the branching ratio? I



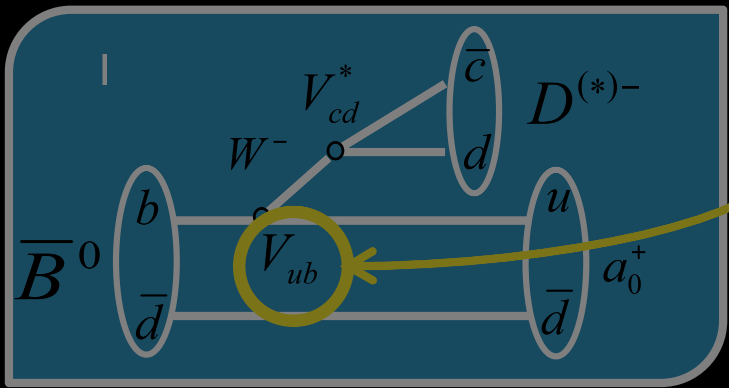


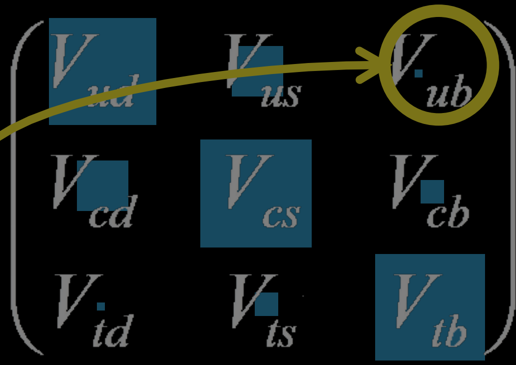
Using

$$\langle D a_0 | B \rangle =$$
$$\langle D | 0 \rangle \times \langle a_0 | B \rangle$$

amplitude small due to Vub ~ 10^{-6}

So how large is the branching ratio? II





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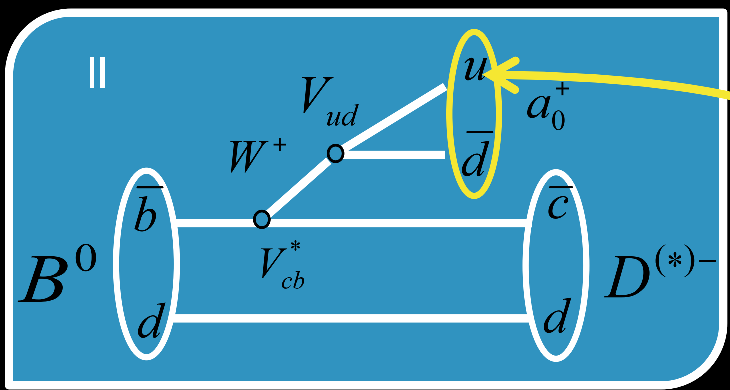


W decay constants

D^+	D^{*+}	a_0^+
200	300	1.1

Using

$$\langle D a_0 | B \rangle =$$
$$\langle a_0 | 0 \rangle \times \langle D | B \rangle$$

amplitude small due

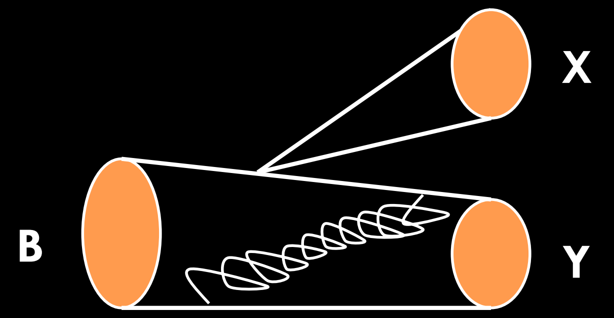
decay constant ~**10^{-6}**

Using $\langle D a_0 | B \rangle = \langle D | 0 \rangle \times \langle a_0 | B \rangle$ is that correct?

In short…

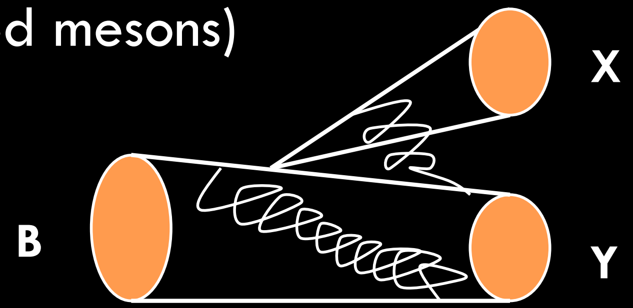
It means we use factorization principles

No interactions between produced mesons XY



Non-factorizing terms (with interactions produced mesons)

usually small …..



…. but not in case of $B^0 \to D^{(*)+} a_0^-$

Naïve prediction: 3 x10^{-6}

Including calculable non-factorizing terms: 6 x10^{-6}

Diehl, Hiller: JHEP 0106:067,2001

Recap

Punch line is:

We search for the $B^0 \rightarrow D^{(*)+} a_0^-$ decay
We are looking for a needle in a haystack.

If we don't find it

- ✓ we can eliminate non-factorizing QCD scenario's

If we do

- ✓ we can eliminate other non-factorizing QCD scenario's
- ✓ measure CKM angle γ with high precision (potentially)

Decay reconstruction

- Lineshape width of a_0 uncertain: PDG 50 -100 MeV
- Setup selection no criteria linewidth: a priori select $B^0 \to D^{(*)+}\eta\pi^-$ events
- Use likelihood fit to discriminate resonant from non-resonant decay
- 6 D decay modes for statistics selection and fit separate; different S/B

$B^0 \to D^+ a_0^-$ $\quad a_0^{22}$® ΓM

$D^+ \to K^+\pi^+\pi^-$ $\quad \Gamma$B®B

$K_s^0\pi^+$

$B^0 \to D^{*+} a_0^-$

$D^{*+} \to D^0\pi^+$

$D^0 \to K^+\pi^-$

$K^+\pi^-\pi^0$

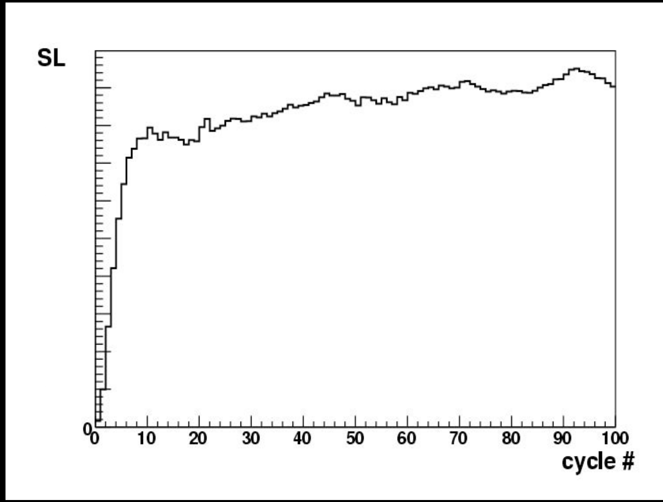
$K^+\pi^-\pi^+\pi^-$

$K_s^0\pi^-\pi^+$

- Non-resonant $B^0 \to D^{(*)+}\eta\pi^-$ decays not measured before: interesting on its own!

Signal selection optimization

- Defined 30 discriminatory observables
  - Particle properties m/p/E
  - Decay lengths (D/K_s)
  - Event shape
  - Utilize angular properties in decay
- 27 for event selection / 3 for likelihood fit



- Cuts are optimized while branching ratio is unknown!!

  using significance:

$$SL = \frac{\varepsilon_S}{(n\sigma/2) + \sqrt{B}}$$

signal selection efficiency

desired observation significance

background events

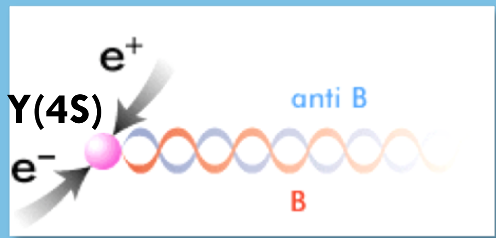
- Simultaneous optimization searches for highest *SL* using rectangular box cuts

Punzi (2003) physics/0308063

Unbinned likelihood fit in 3 dimensions

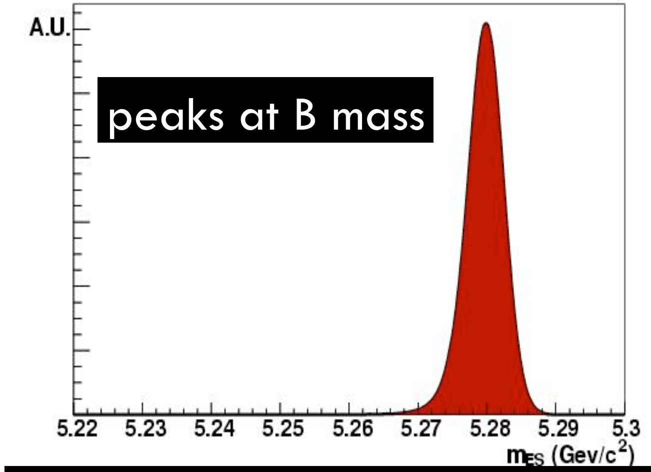
1. ***M_{ES}*** beam energy substituted mass, $m_{ES} = \sqrt{E_{beam}^{*2} - p_B^2}$
   signal peaks at B mass, background as Argus shape

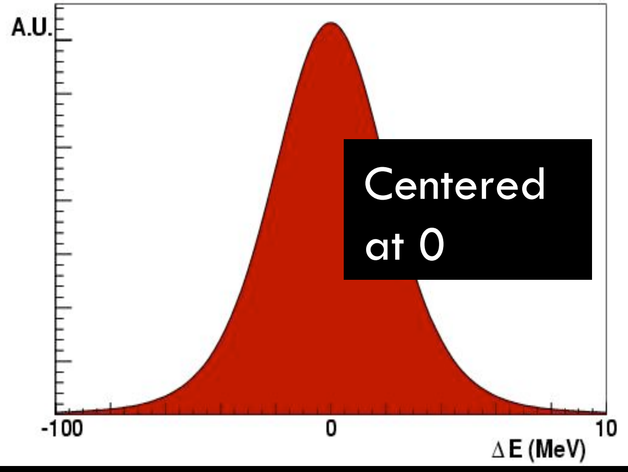
2. ***ΔE*** energy difference, $\Delta E = E^{*} - E_{beam}^{*}$
   signal peaks at 0, background flat

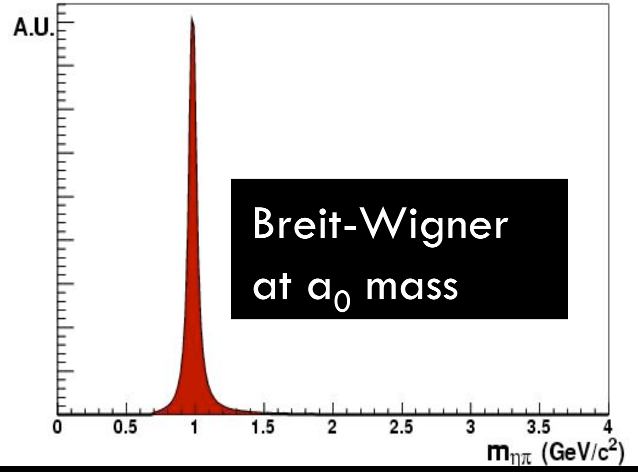


3. ***Mηπ*** –invariant mass,
   resonant signal is Breit-Wigner, non resonant as phase space with kinematics

PDF shapes signal



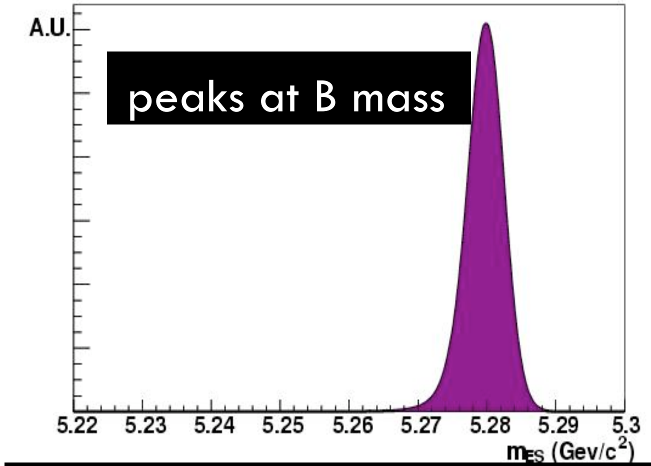


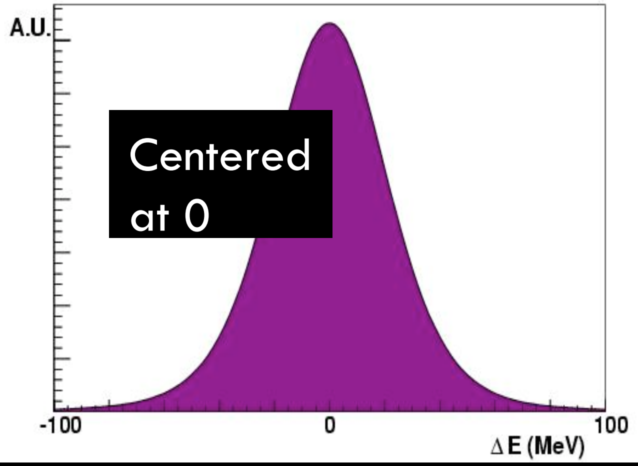


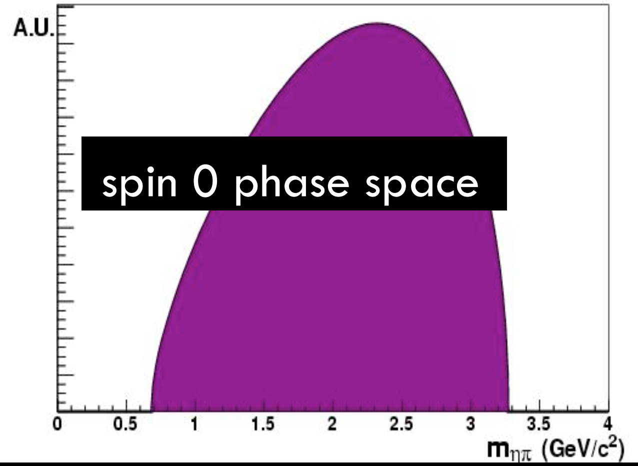
M_{ES} ΔE $M_{\eta\pi}$

PDF shapes non-resonant signal

M_{ES} ΔE $M_{\eta\pi}$

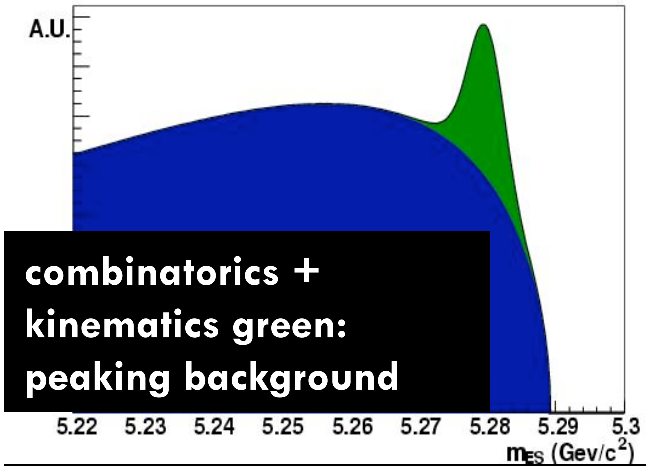




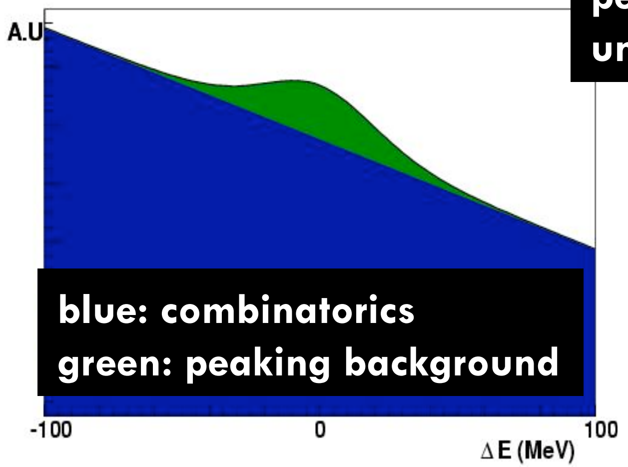


PDF shapes background

M_{ES} | ΔE | $M_{\eta\pi}$

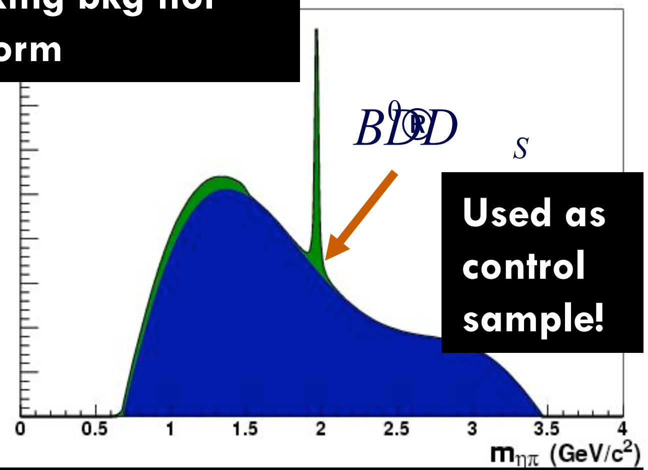


combinatorics + kinematics green: peaking background



blue: combinatorics
green: peaking background

peaking bkg not uniform



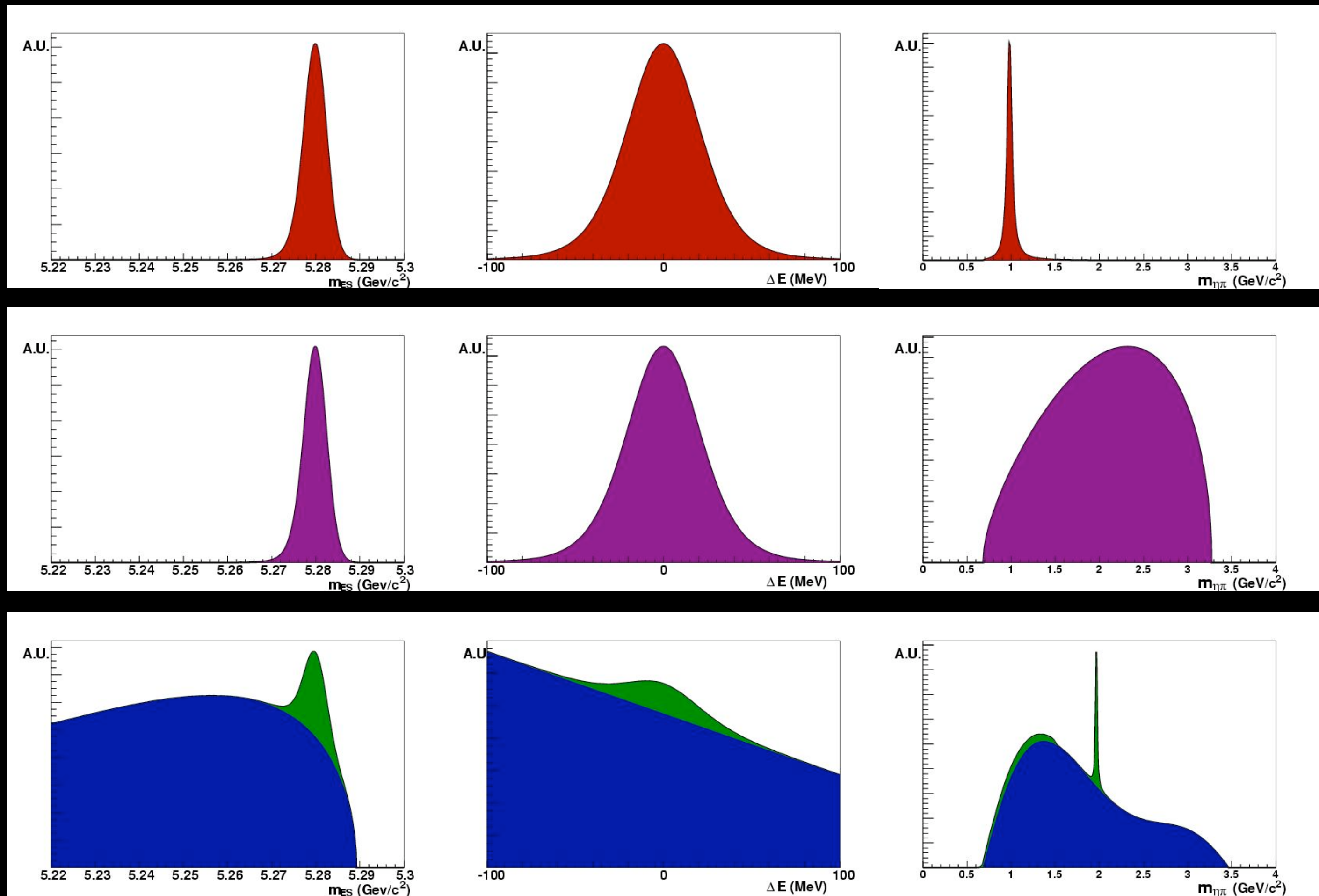
Used as control sample!

PDF shapes summary

$B^0 \to D^+ a_0^-$

$B^0 \to D^+ \eta\pi^-$

background



Shape parameters determined on MC and fixed in the fit to data

Adding the different D decay modes

5 parameters fitted in likelihood fit for every D decay mode :

1.(# resonant signal events) **BR(resonant)**
2.(# non-resonant signal events) **BR(non-resonant)**
3.# Ds events
4.# BB background events
5.# qq background events

$$\mathcal{B}(B \to D a_0) \times \mathcal{B}(a_0 \to \eta\pi) = N_{obs,i} \frac{1}{N_{BB} \times B(D)_i \times \varepsilon_{eff,i}}$$

Combine D^+ and D^{*+} decay modes

1. Simultaneous fit of branching ratios of $B^0 \to D^+ a_0^-$ and $B^0 \to D^+ \eta\pi^-$
2. Other 3 parameters fitted individually.

$B^0 \to D^+ a_0^-$

$D^+ \to K^+\pi^+\pi^-$

$K_s^0\pi^+$

$B^0 \to D^{*+} a_0^-$

$D^{*+} \to D^0\pi^+$

$D^0 \to K^+\pi^-$

$K^+\pi^-\pi^0$

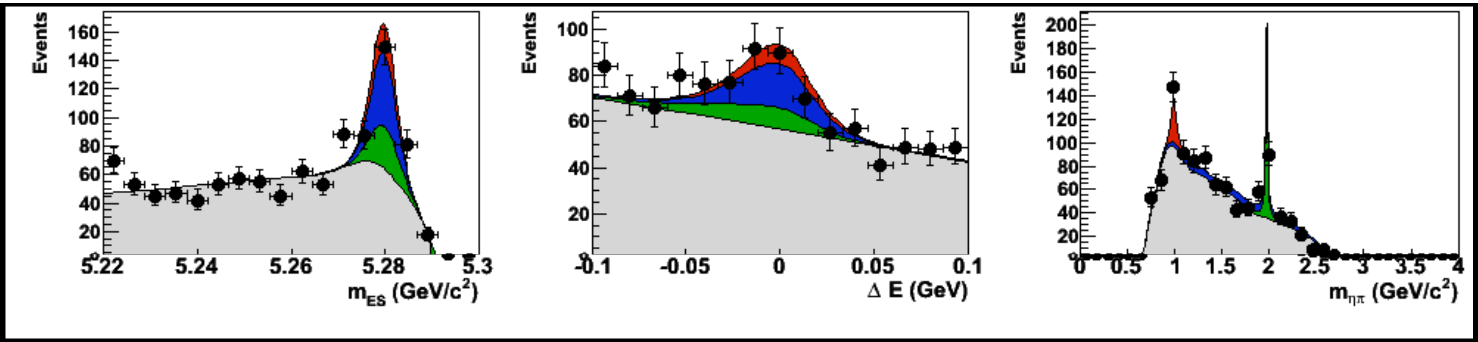
$K^+\pi^-\pi^+\pi^-$

$K_s^0\pi^-\pi^+$

Combined Fit Result

30	$B^0 \rightarrow D^{*+} a_0^-$
76	$B^0 \rightarrow D^{*+} \eta\pi^-$
50	$B^0 \rightarrow D^{*+} D_s^-$

Full projection



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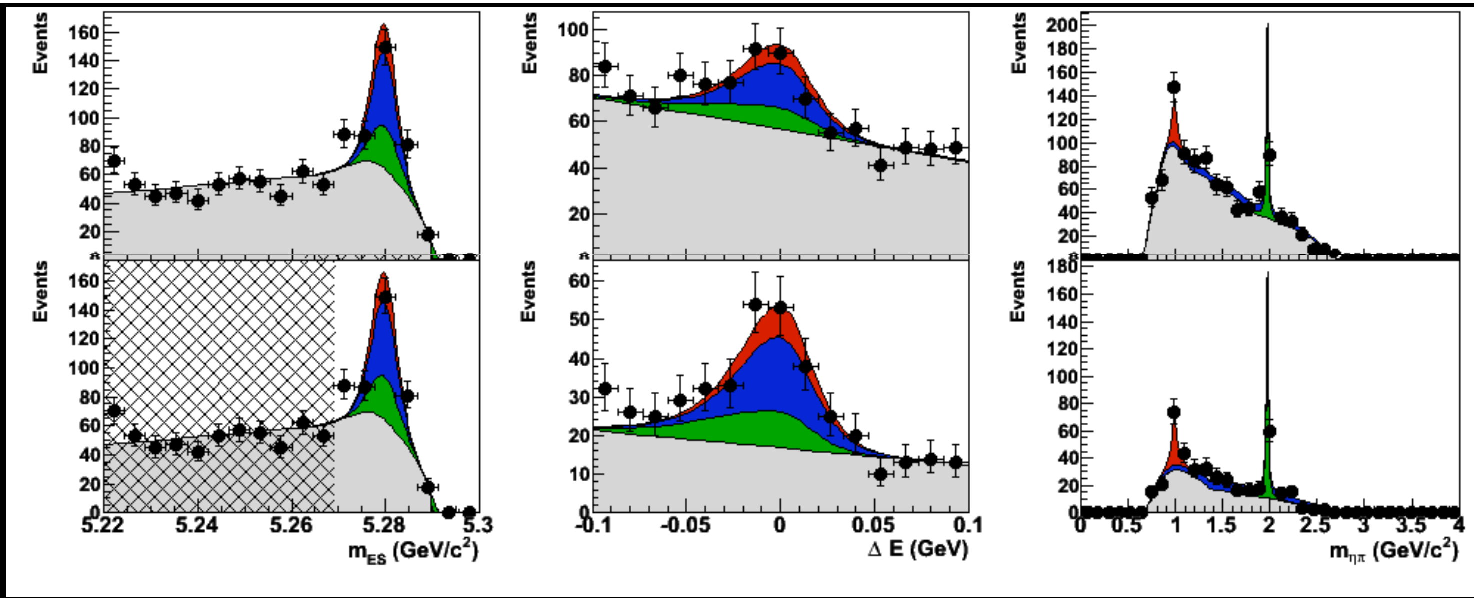
Full projection

M_{ES} signal reg



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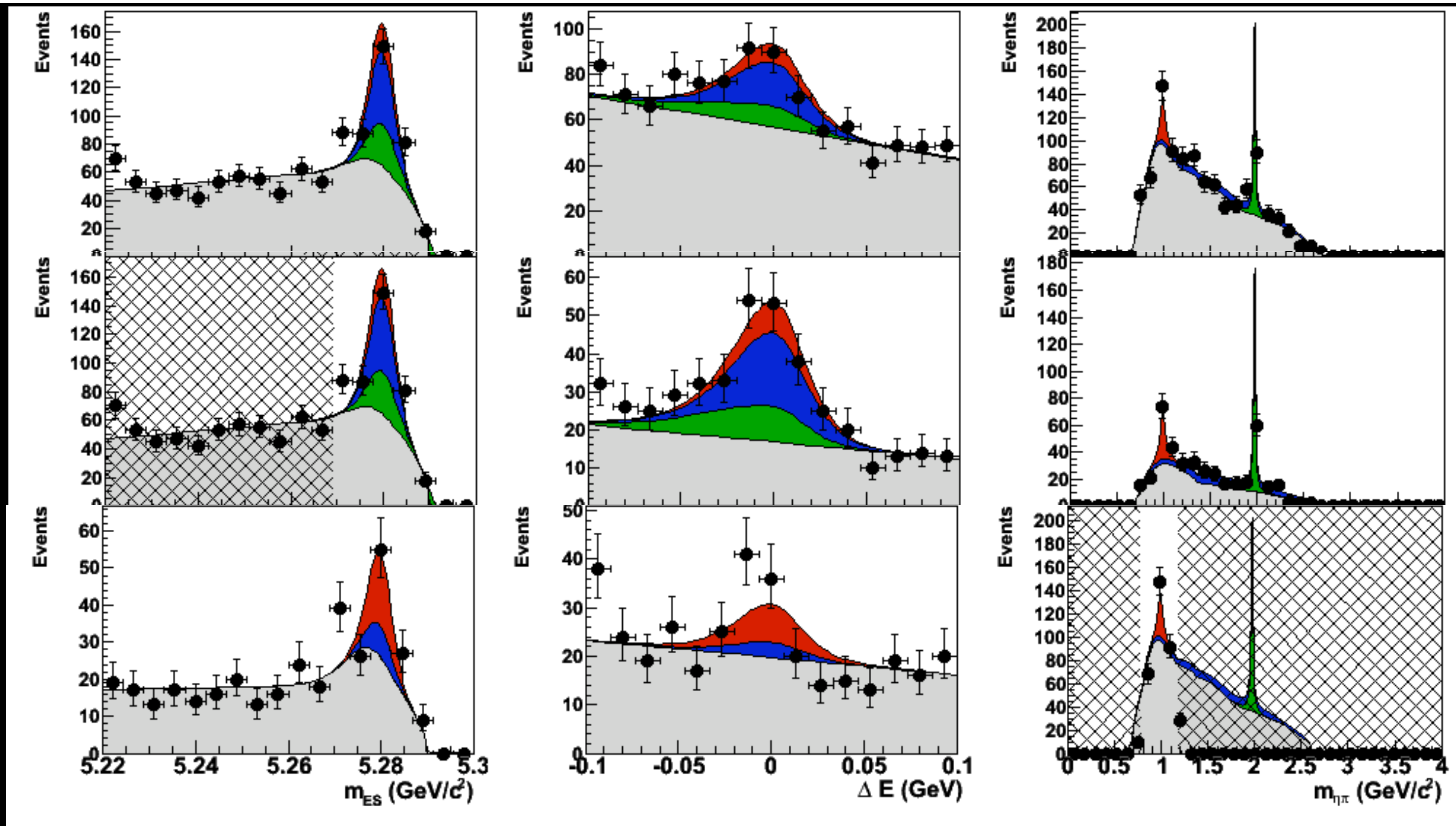
Full projection

M_{ES} signal reg

$M_{\eta\pi}$ signal reg



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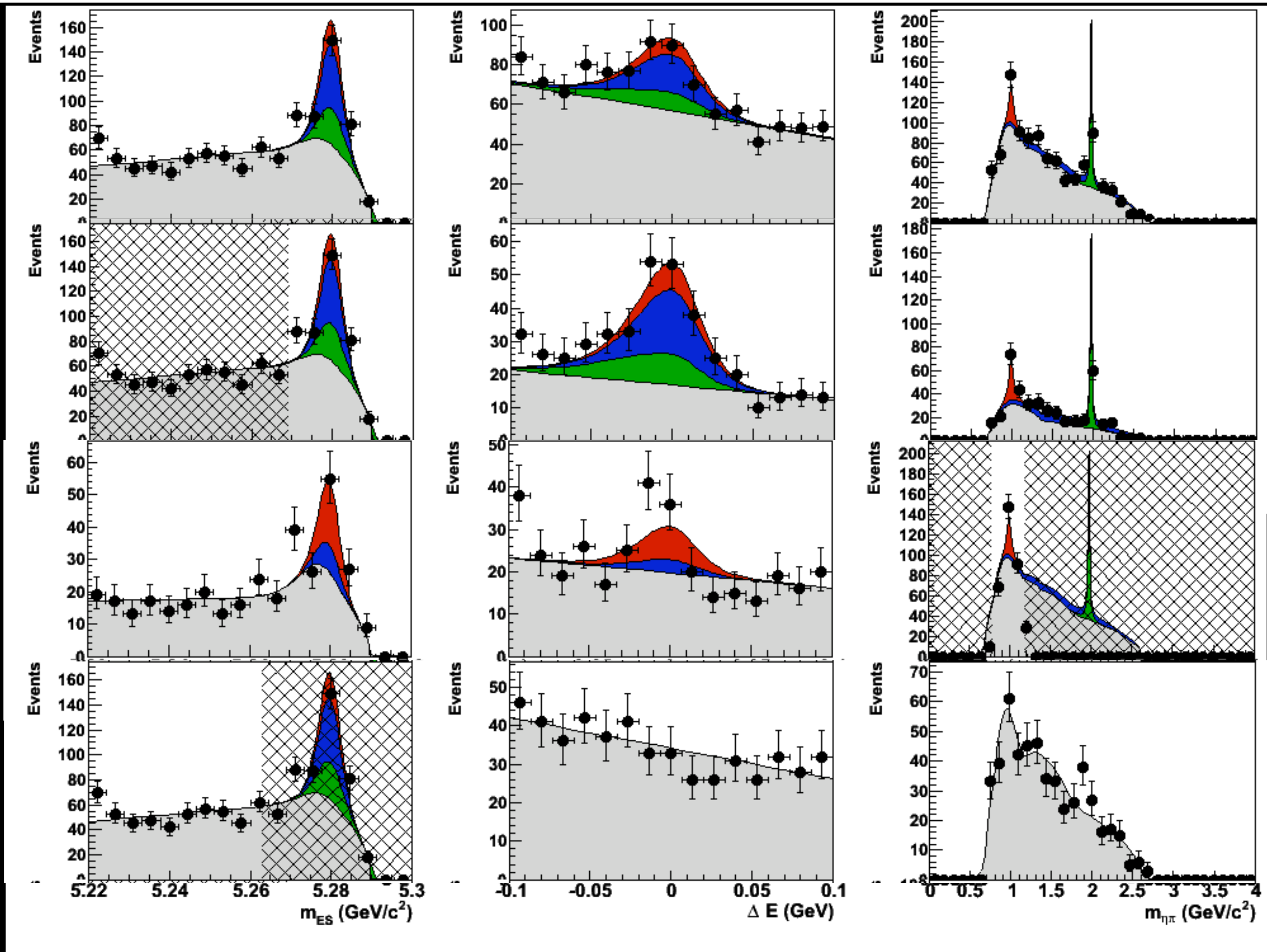
Full projection

M_{ES} signal reg

$M_{\eta\pi}$ signal reg

M_{ES} side region



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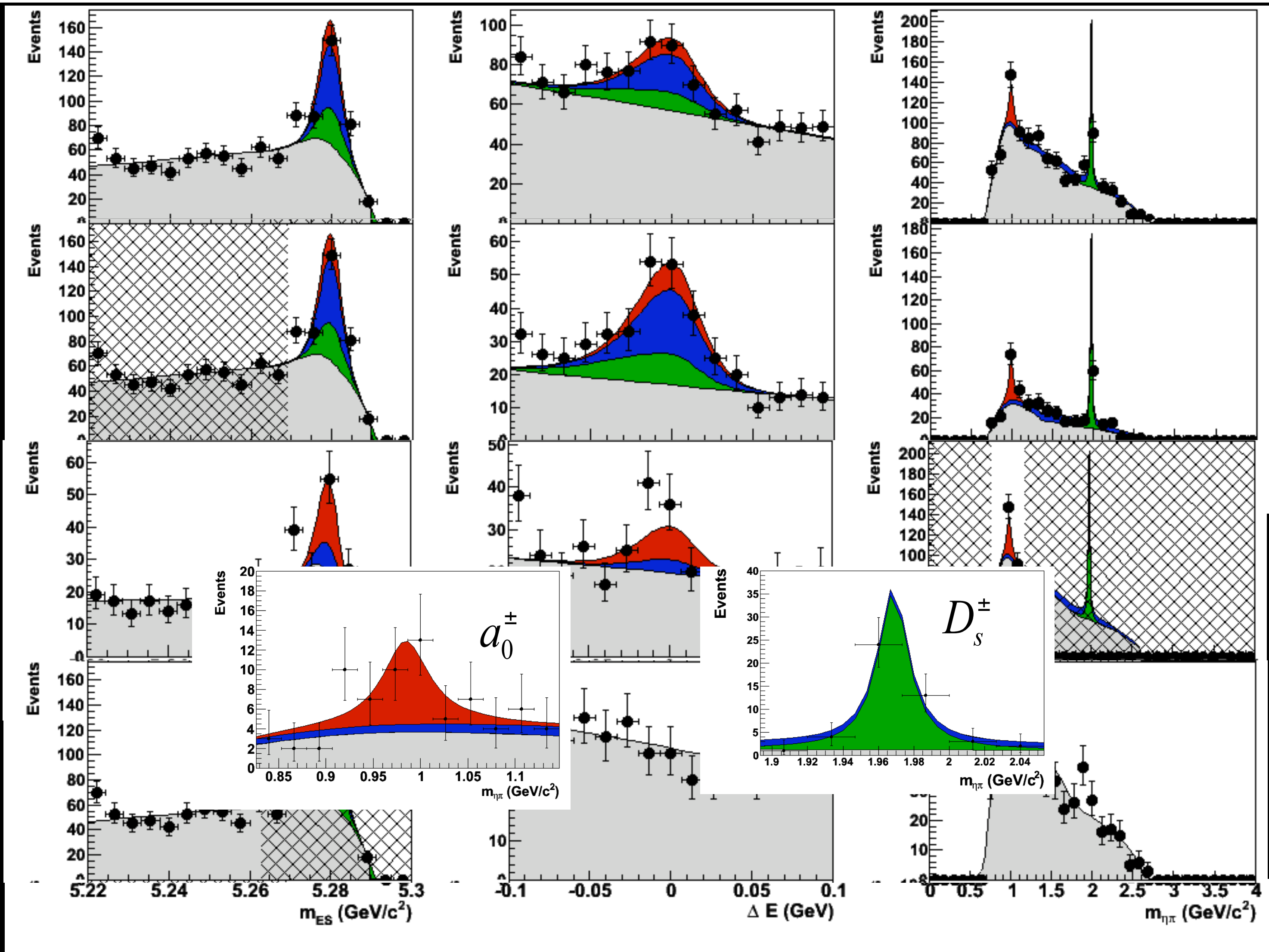
Full projection

M_{ES} signal reg

$M_{\eta\pi}$ signal reg

M_{ES} side region



Systematic uncertainties

- Determined using:
  - Full Monte Carlo studies
  - Toy Monte Carlo studies
  - Data sample itself
  - Control sample $B^0 \rightarrow D^{(*)+} D_s^-$
- Largest uncertainties due to a_0 line-shape and selection validations

Syster

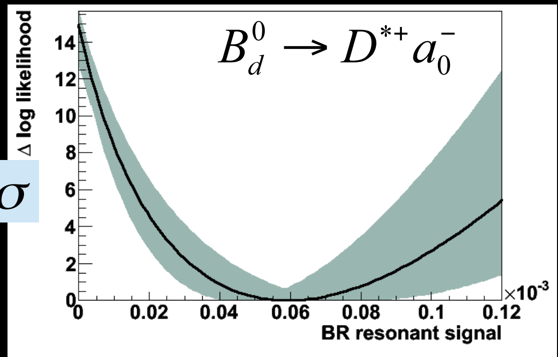
- Determ
  - Full M
  - Toy M
  - Data
  - Contr
- Largest selectio

source	$D^{\pm}$ modes: DchI	DchII	$D^{*\pm}$ modes: DstI	DstII	DstIII	DstIV
Resonant signal specific errors						
observed number of events						
bias offset (a.v.)	2.7	1.8	1.3	0.5	0.9	0.5
observed branching ratio						
Γ_{a_0} (a.v)	$2.7 \cdot 10^{-6}$		$4.0 \cdot 10^{-6}$			
m_{a_0} (a.v.)	$5.3 \cdot 10^{-8}$		$4.5 \cdot 10^{-8}$			
$m_{\eta\pi}$ eff. (a.v.)	$3.2 \cdot 10^{-7}$		$3.8 \cdot 10^{-7}$			
p.d.f. shape (a.v)	$2.9 \cdot 10^{-7}$		$3.7 \cdot 10^{-7}$			
Non-resonant signal specific errors						
observed number of events						
bias offset (a.v.)	8.3	8.2	3.7	2.5	4.6	3.0
observed branching ratio						
Γ_{a_0} (a.v)	$8.4 \cdot 10^{-8}$		$6.7 \cdot 10^{-7}$			
m_{a_0} (a.v.)	$5.6 \cdot 10^{-8}$		$5.4 \cdot 10^{-8}$			
$m_{\eta\pi}$ eff. (a.v.)	$5.3 \cdot 10^{-7}$		$1.4 \cdot 10^{-6}$			
p.d.f. shape (a.v)	$7.2 \cdot 10^{-7}$		$8.0 \cdot 10^{-7}$			
Common errors						
number of B events						
B counting (%)	1.1		1.1			
fractional D decay						
$D^{(*)\pm}$ decay (%)	3.6	4.1	2.1	4.6	3.4	25.8
efficiency						
π^0 ID (%)	–	–	–	3.5	–	–
K^0_s ID (%)	–	0.5	–	–	–	0.5
η ID (%)	3		3			
tracking (%)	5.4	4.2	5.5	5.4	8.2	5.6
selection (%)	10		10			

Profile likelihood

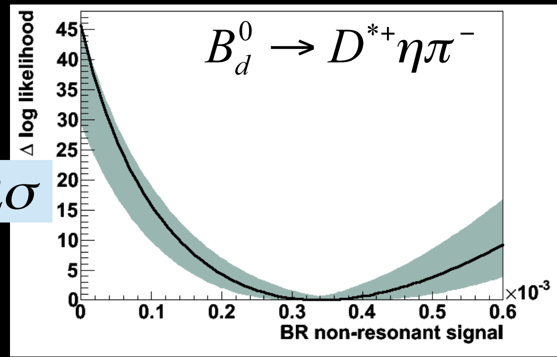
D* meson modes

5.3σ



$(5.93^{+1.64+2.22}_{-1.48-1.52}) \cdot 10^{-5}$

8.2σ

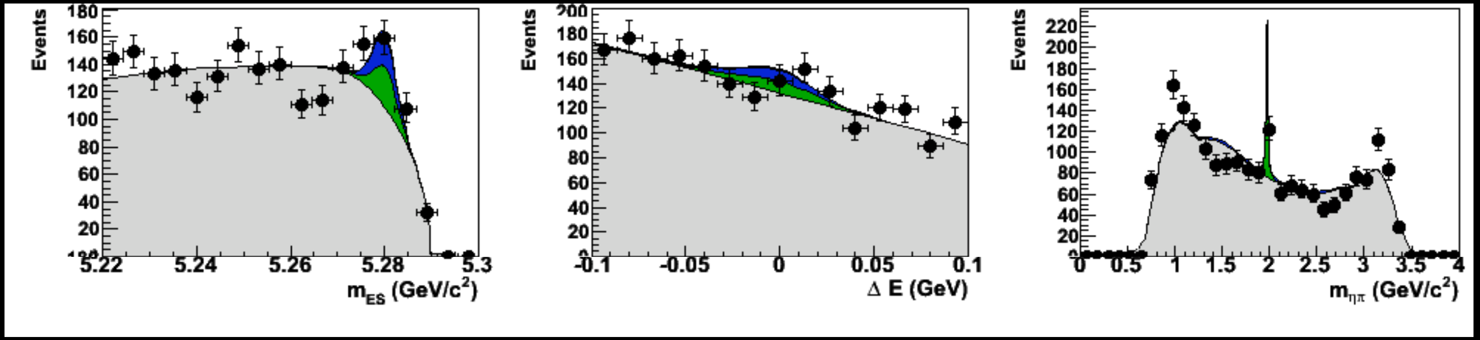


$(33.91^{+5.47+6.80}_{-5.11-5.14}) \cdot 10^{-5}$

Combined Fit Result

-5	$B^0 \to D^+ a_0^-$
46	$B^0 \to D^+ \eta\pi^-$
52	$B^0 \to D^+ D_s^-$

Full projection

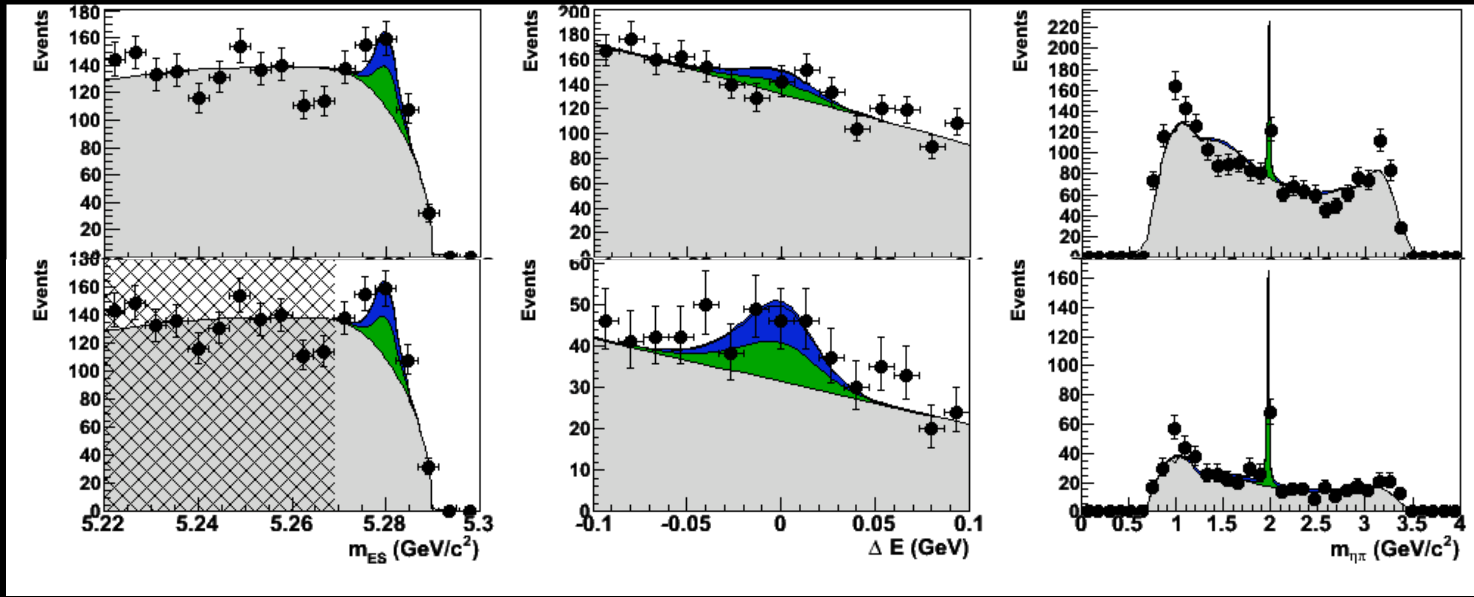


Combined Fit Result

-5	$B^0 \to D^+ a_0^-$
46	$B^0 \to D^+ \eta\pi^-$
52	$B^0 \to D^+ D_s^-$

Full projection

M_{ES} signal reg



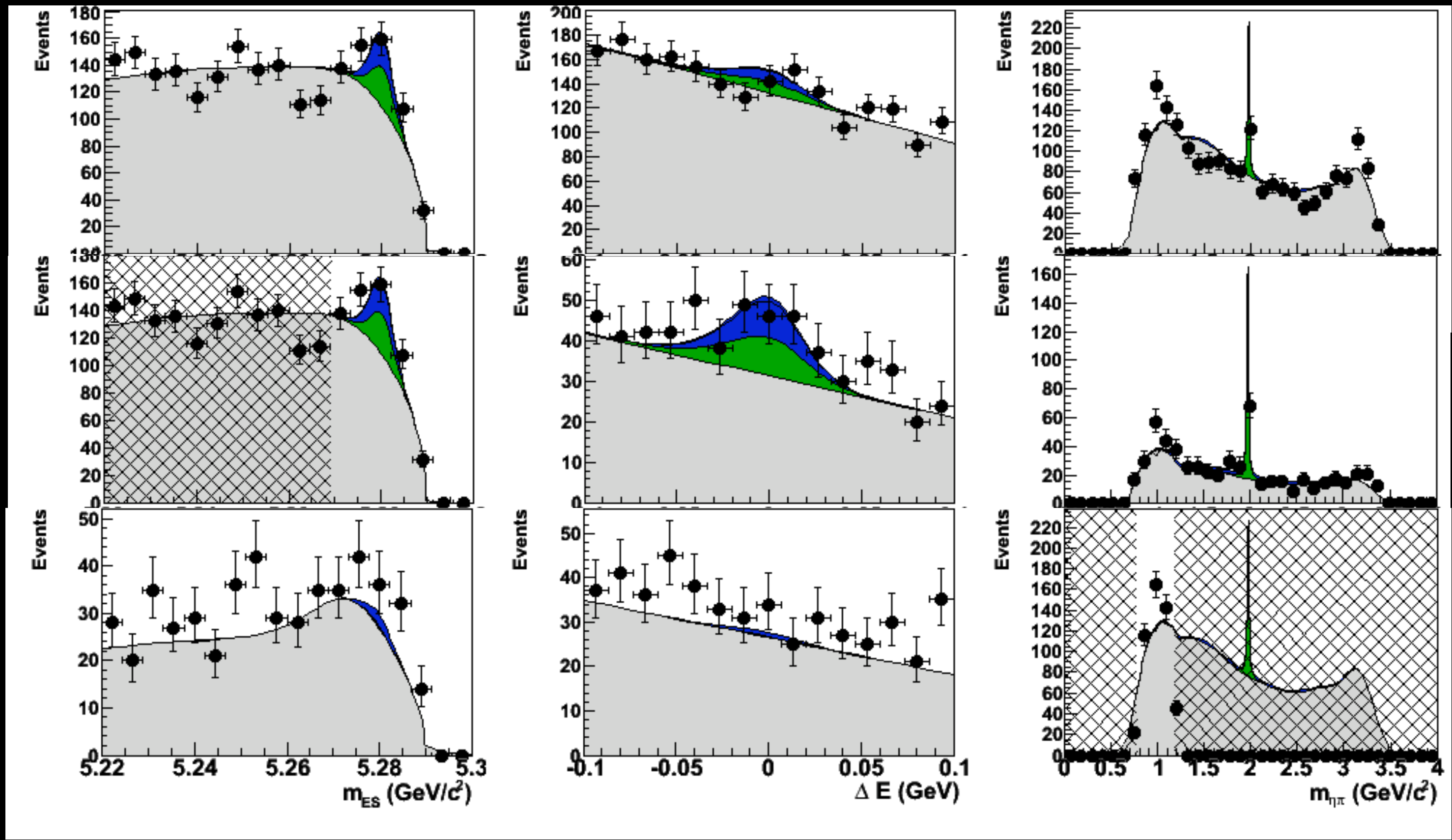
Combined Fit Result

-5	$B^0 \to D^+ a_0^-$
46	$B^0 \to D^+ \eta\pi^-$
52	$B^0 \to D^+ D_s^-$

Full projection

M_{ES} signal reg

$M_{\eta\pi}$ signal reg



Combined Fit Result

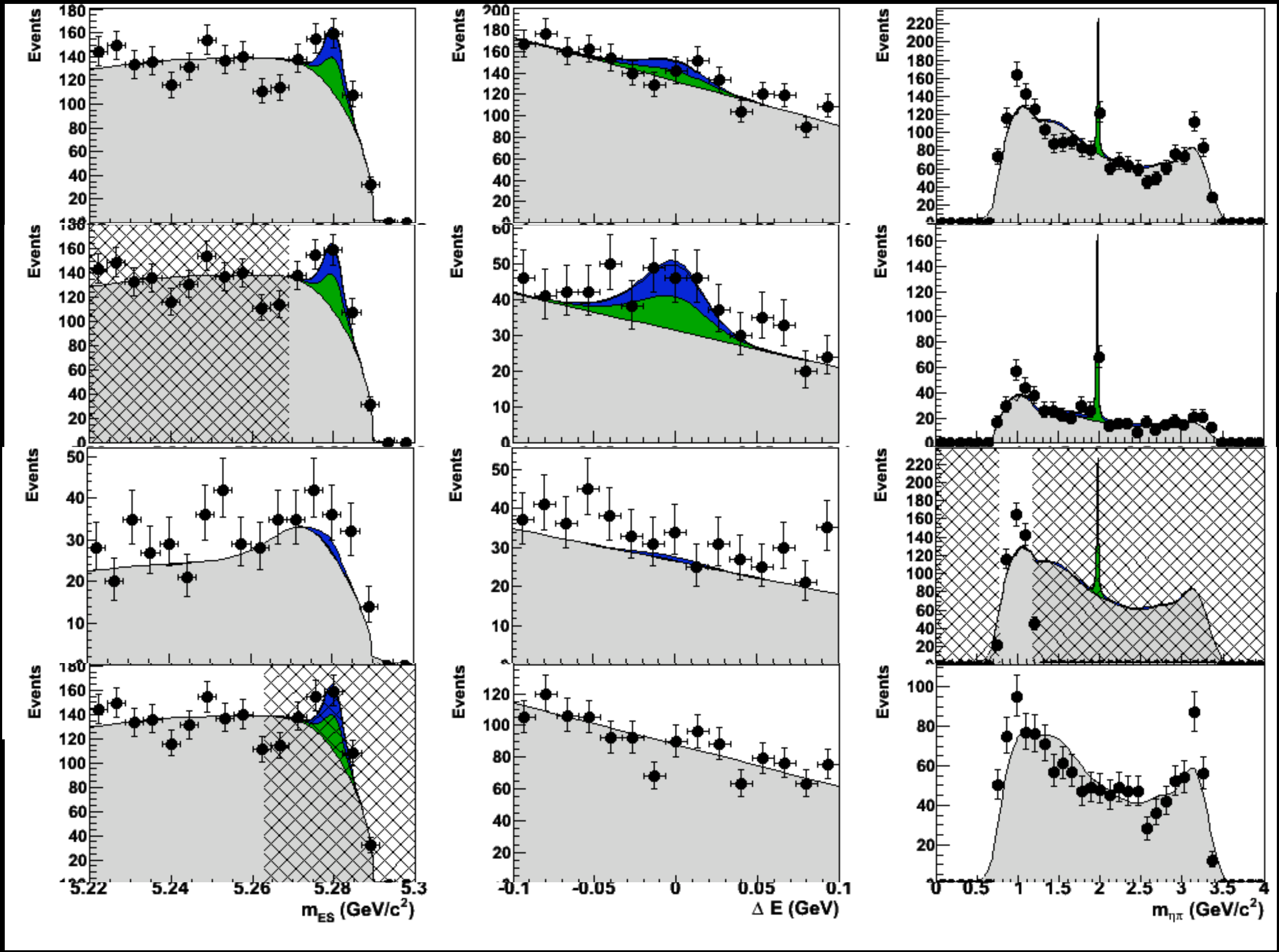
-5	$B^0 \to D^+ a_0^-$
46	$B^0 \to D^+ \eta\pi^-$
52	$B^0 \to D^+ D_s^-$

Full projection

M_{ES} signal reg

$M_{\eta\pi}$ signal reg

M_{ES} side region



Combined Fit Result

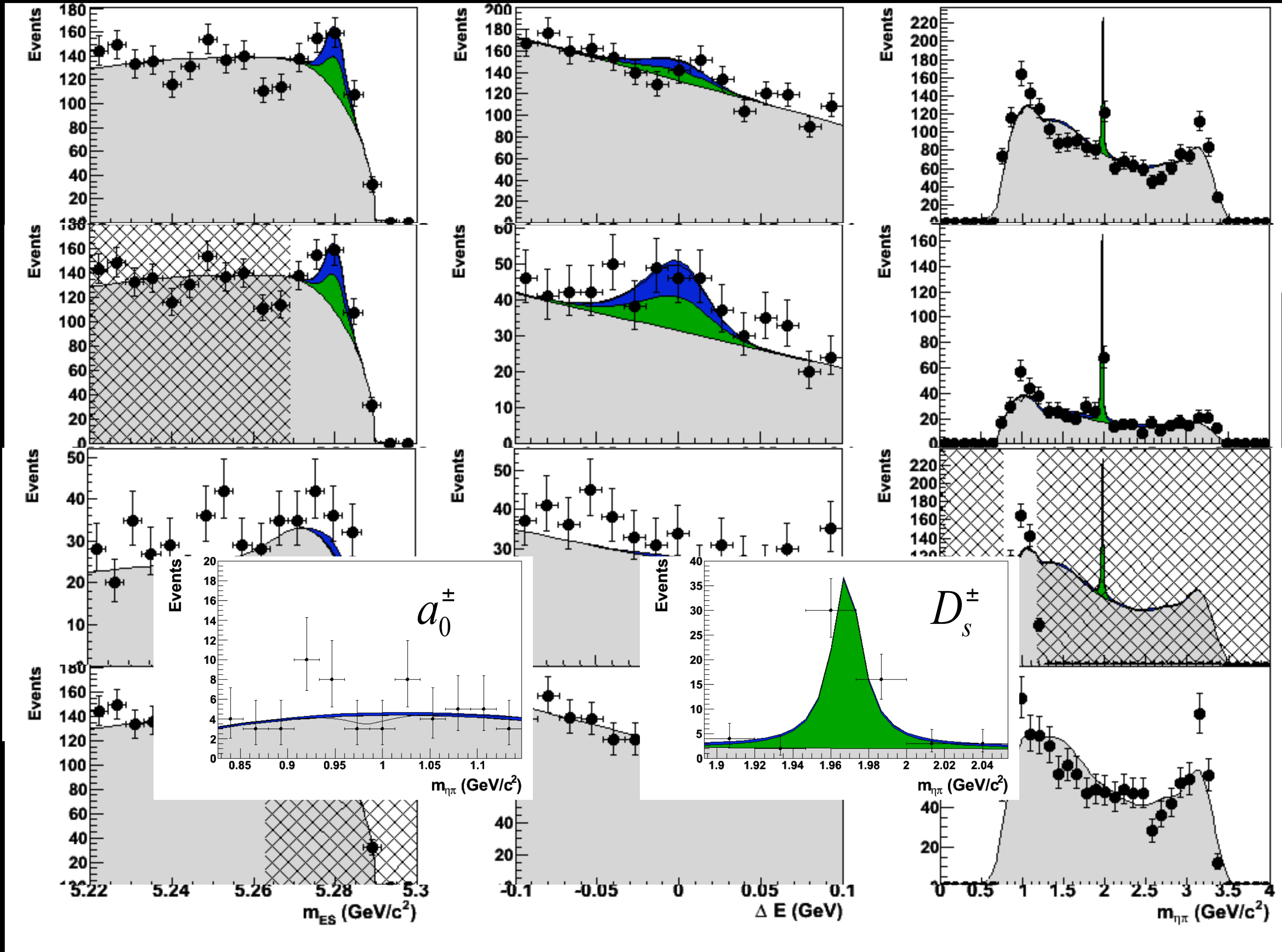
-5	$B^0 \to D^+ a_0^-$
46	$B^0 \to D^+ \eta\pi^-$
52	$B^0 \to D^+ D_s^-$

Full projection

M_{ES} signal reg

$M_{\eta\pi}$ signal reg

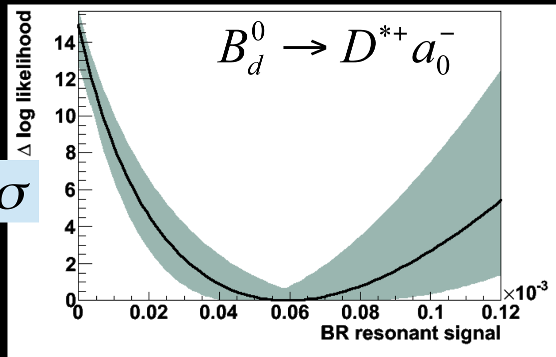
M_{ES} side region



Profile likelihood

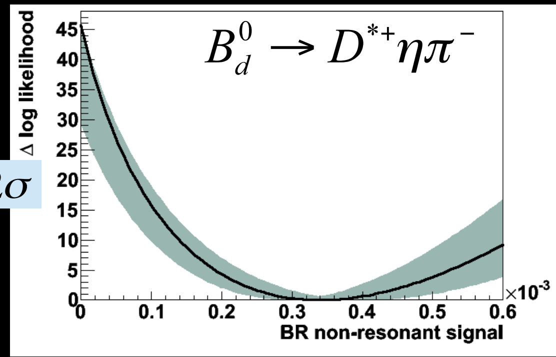
D* meson modes

5.3σ



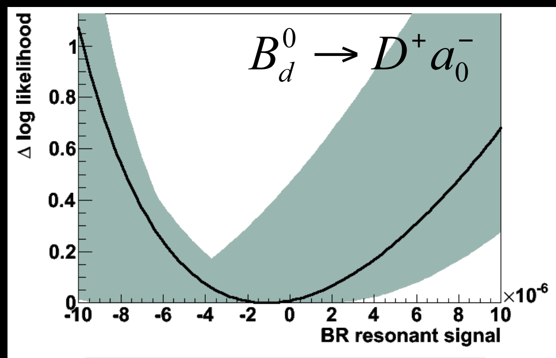
$(5.93^{+1.64+2.22}_{-1.48-1.52}) \cdot 10^{-5}$

8.2σ



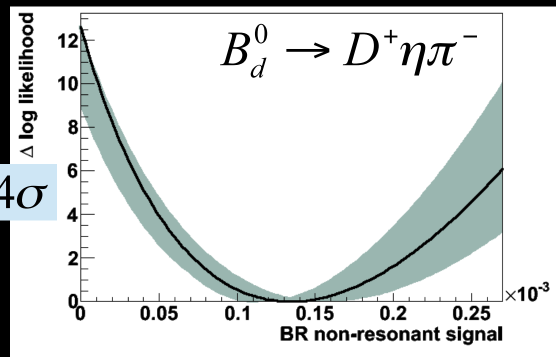
$(33.91^{+5.47+6.80}_{-5.11-5.14}) \cdot 10^{-5}$

D meson modes



$(-0.11^{+0.93\,+0.29}_{-0.67-0.76}) \cdot 10^{-5}$

4.4σ

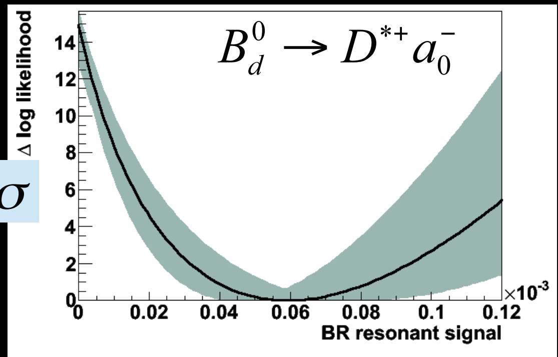


$(13.41^{+3.54+2.42}_{-3.25-1.94}) \cdot 10^{-5}$

Profile likelihood

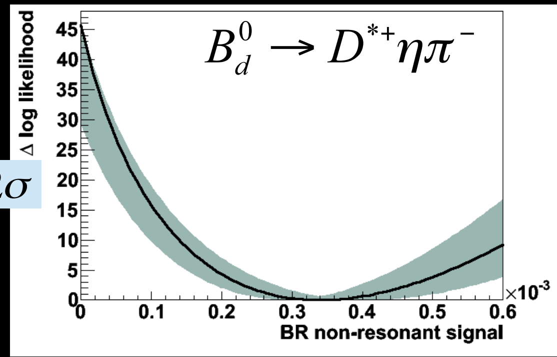
D* meson modes

5.3σ



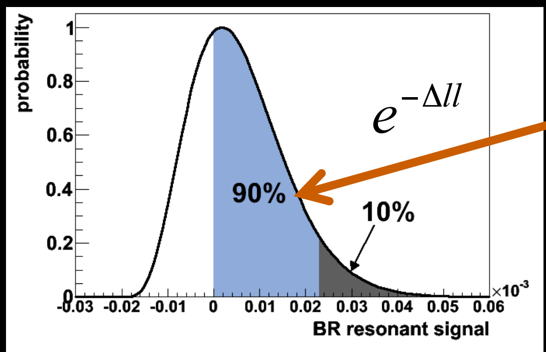
$(5.93^{+1.64+2.22}_{-1.48-1.52}) \cdot 10^{-5}$

8.2σ

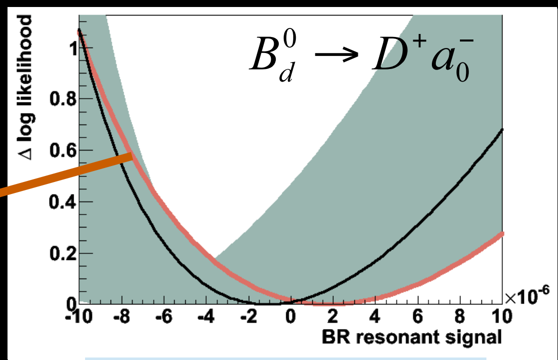


$(33.91^{+5.47+6.80}_{-5.11-5.14}) \cdot 10^{-5}$

D meson modes

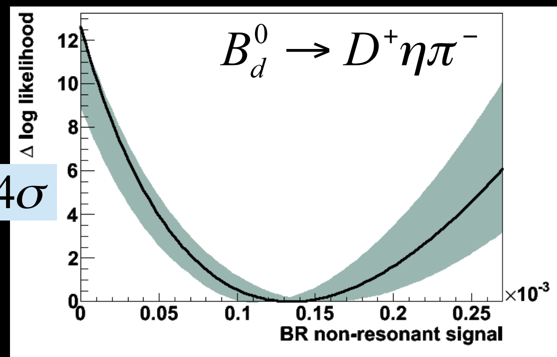


$< 2.3 \cdot 10^{-5}$ @90% c.l.



$(-0.11^{+0.93+0.29}_{-0.67-0.76}) \cdot 10^{-5}$

4.4σ



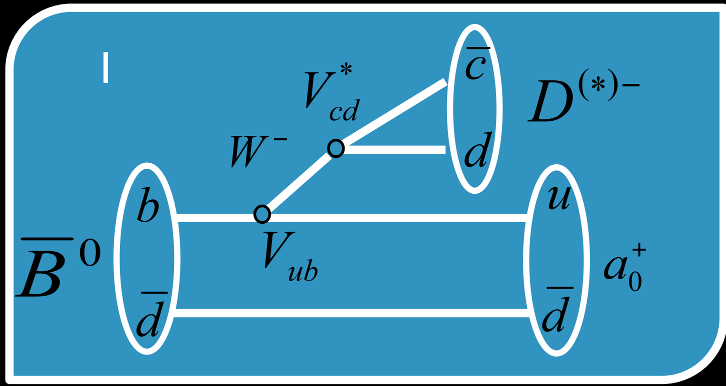
$(13.41^{+3.54+2.42}_{-3.25-1.94}) \cdot 10^{-5}$

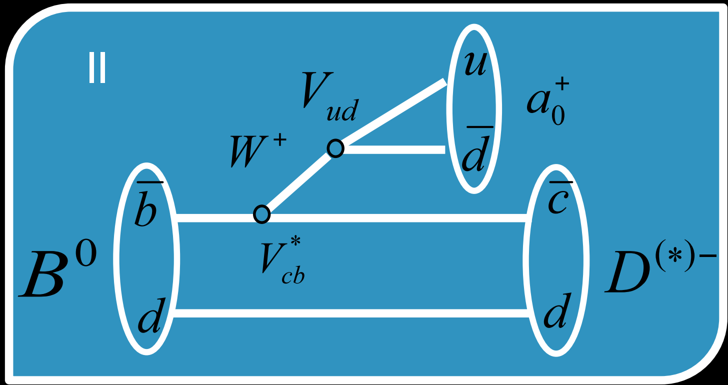
Intermediate results

- Branching ratio of $B^0 \to D^{(*)+} a_0^-$ predicted (3-6) 10^{-6}
- Analysis setup
  - Data selection optimization using ~30 variables
  - Likelihood fit in 3 observables
- Measured branching ratios
  - Non-resonant $B^0 \to D^+ \eta \pi^-$ 1.3 10^{-5} at 4 σ (46 events)
    $B^0 \to D^{*+} \eta \pi^-$ 3.4 10^{-5} at 8 σ (76 events)
  - Resonant $B^0 \to D^{*+} a_0^-$ 6.0x10^{-5} at 5 σ (30 events)
    $B^0 \to D^+ a_0^-$ > 2.3x10^{-5} at 90 % CL
- Not enough for time-dependent analysis needed to measure γ (?)

Possible explanation higher BR

- We measure
  $B^0 \rightarrow D^{*+} a_0^-$ 6.0x10^{-5} at 5 σ (30 events)
- Naïve factorization model predicts
  3x 10^{-6}
- Including some QCD diagrams upper limit at
  6x 10^{-6}
- Restrictions on both naïve factorizable diagrams strict!





Possible explanation higher BR

- We measure
  $B^0 \rightarrow D^{*+} a_0^-$ 6.0x10^{-5} at 5 σ (30 events)
- Naïve factorization model: 3x 10^{-6}
- Adding QCD diagrams: upper limit 6x10^{-6}
- Restrictions on both naïve factorizable diagrams strict!

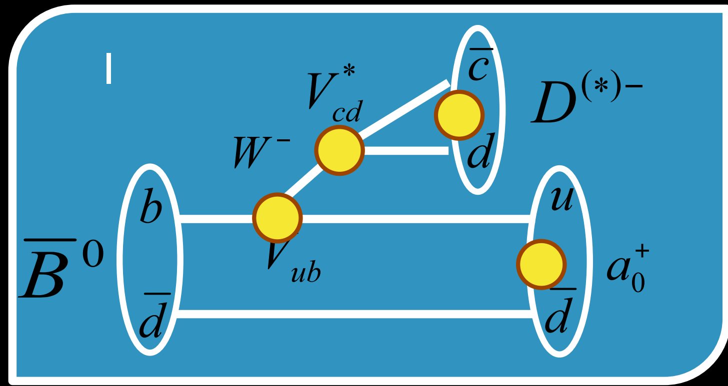
For naïve calculation we need to know:

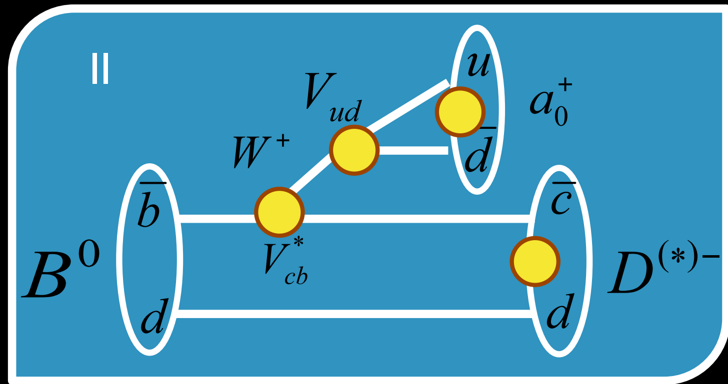
CKM V_{ub} V_{cd} V_{cb} V_{ud}

W decay f_D fa_0

B decay $F_{B \rightarrow D}$ $F_{B \rightarrow a}$

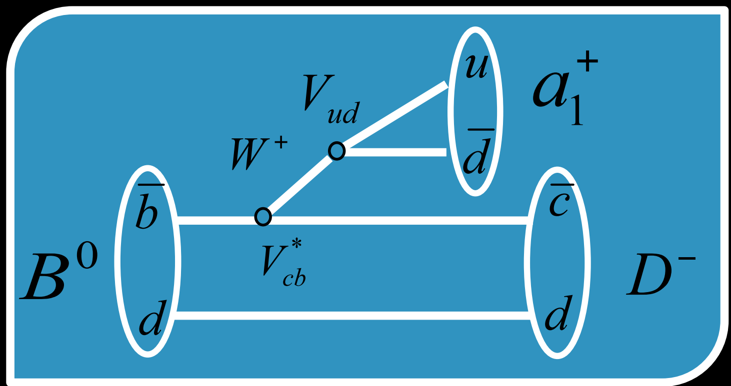
All well known or strong upper limit



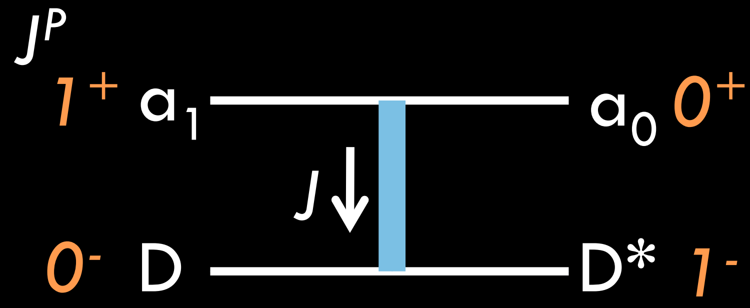


- Ratio I/II measured in time-dependent analysis (cosine term)

Rescattering



+



BF $B^0 \to D^+ a_1^-$ $(6.0 \pm 3.3) \times 10^{-3}$

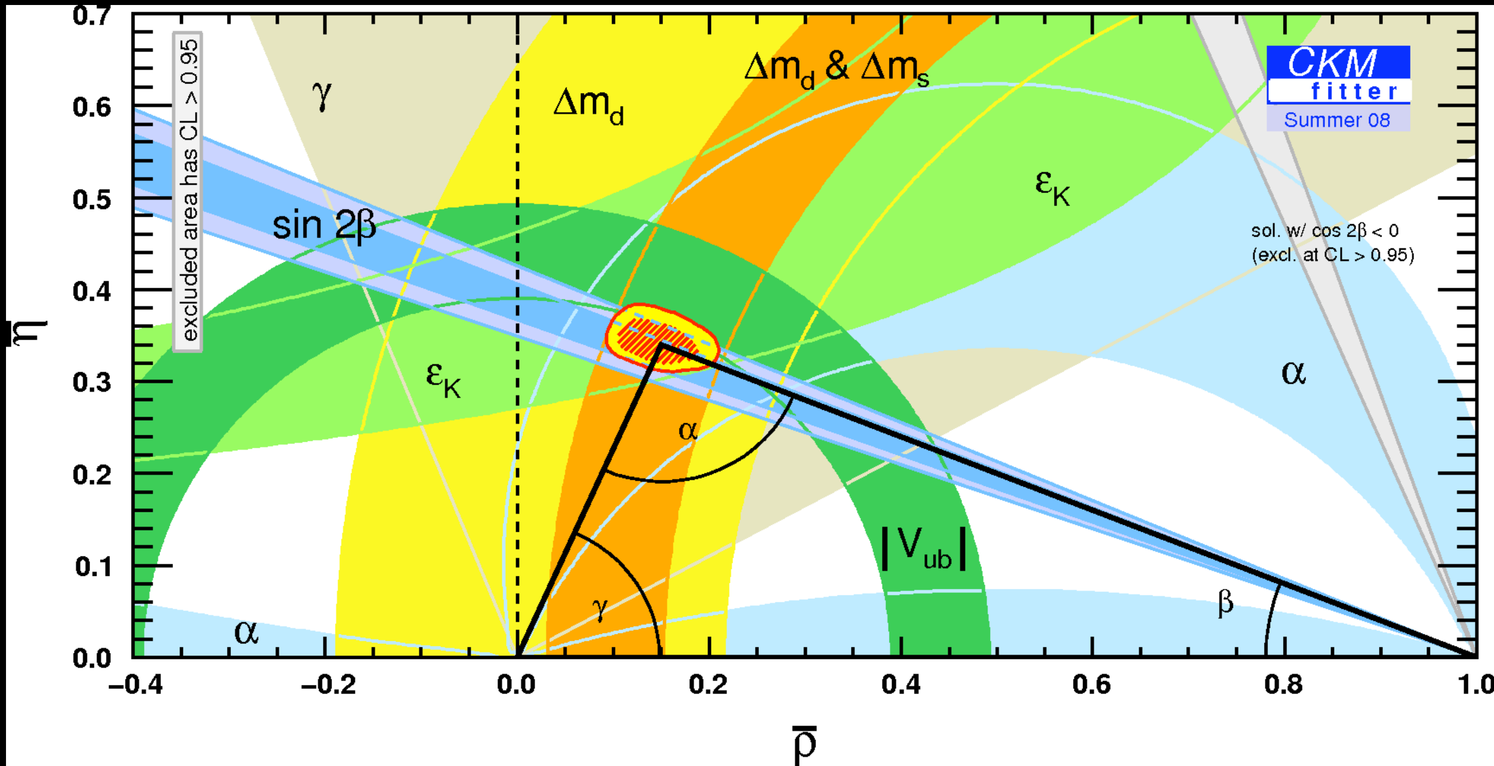
- Possible rescattering through $Da_1 \leftrightarrow D^*a_0$
- Not calculated, comparison with $D\rho \leftrightarrow D^*\pi$ gives order 10^{-6}
- Kinematic arguments: easily would be at order 10^{-5}
- Same CKM phase gamma!

Conclusion

- Branching ratio of $B^0 \rightarrow D^{(*)+} a_0^-$ predicted (3-6) 10^{-6}
- Analysis setup
  - Data selection optimization using ~30 variables
  - Likelihood fit in 3 observables
- Measured branching ratios
  - Non-resonant $B^0 \rightarrow D^+ \eta \pi^-$ 1.3 10^{-5} at 4 σ (46 events)
    $B^0 \rightarrow D^{*+} \eta \pi^-$ 3.4 10^{-5} at 8 σ (76 events)
  - Resonant $B^0 \rightarrow D^{*+} a_0^-$ 6.0x10^{-5} at 5 σ (30 events)
    $B^0 \rightarrow D^+ a_0^-$ > 2.3x10^{-5} at 90 % CL
- Not enough for time-dependent analysis needed to measure γ (?)
- Time dependent analysis will give insight to high BF

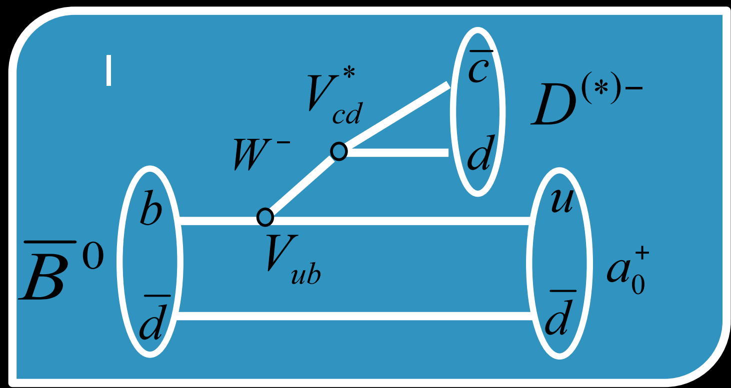
Backup slides

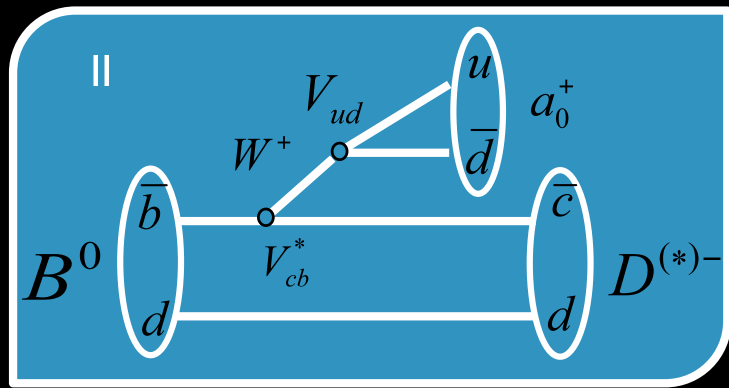
CKM UT current status



Possible explanation higher BR

- Restrictions on both naïve factorizable diagrams strict!
- QCD factorizable diagrams upper limit at 6 10^{-6}, factor 10 too low!
- Possible rescattering through $Da_1 \leftrightarrow D^*a_0$ not calculated, comparison with $D\rho \leftrightarrow D^*\pi$ gives order 10^{-6} but should be larger!! Easily would be at order 10^{-5}.

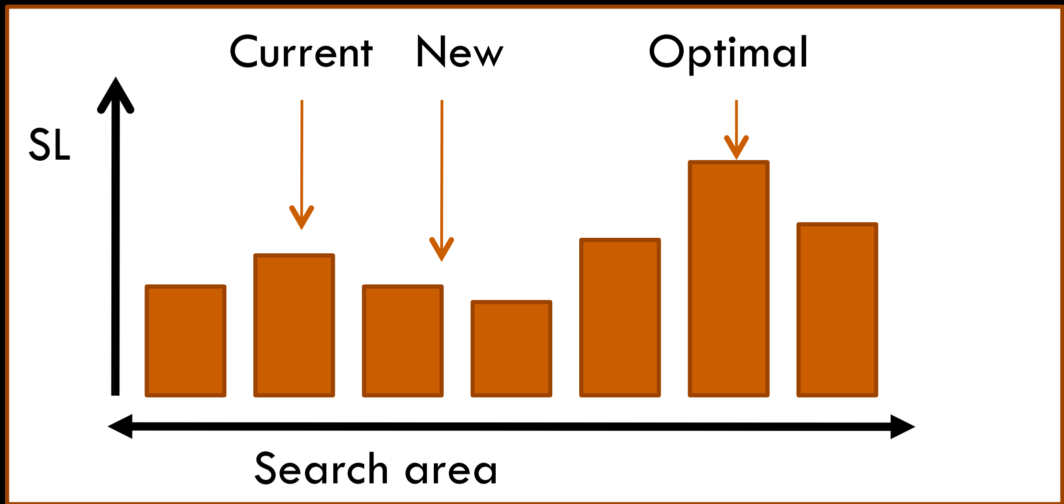


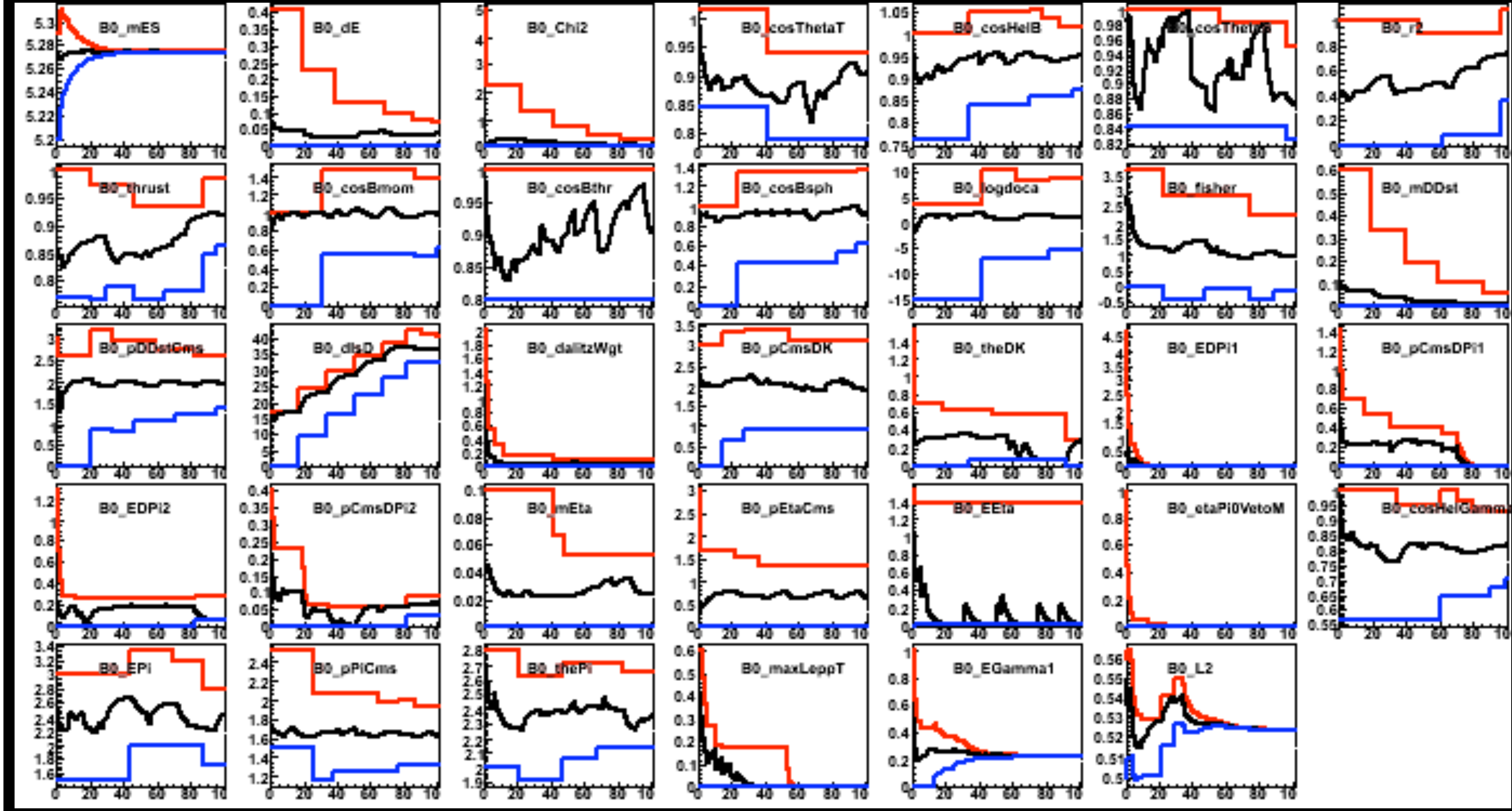


Optimization setup

Per cycle:

- Evaluates significance level in given search area with cuts placed on all other variables.
- New, optimized, cut is placed in direction of the highest SL.
- All variables are evaluated in single cycle




B0_mES
B0_dE
B0_Chi2
B0_cosThetaT
B0_cosHelB
B0_r2
B0_thrust
B0_cosBmom
B0_cosBthr
B0_cosBsph
B0_logdoca
B0_fisher
B0_mDDst
B0_pDDstCms
B0_dlsD
B0_dalitzWgt
B0_pCmsDK
B0_theDK
B0_EDPi1
B0_pCmsDPi1
B0_EDPi2
B0_pCmsDPi2
B0_mEta
B0_pEtaCms
B0_EEta
B0_etaPi0VetoM
B0_EPi
B0_pPiCms
B0_thePi
B0_maxLeppT
B0_EGamma1
B0_L2

a_0 suppression mechanism

G parity suppressed/second class current

- Weak current has *V-A* behaviour
  'natural' spin-parity meson couple to *V*, 'unnatural' to *A*
- $G \equiv C\, e^{i\pi I2}$
- First class currents: *G+* and *V*, or *G-* and *A*
- Second class currents: *G-* and *V*, or *G+* and *A*
- a_0 doubly suppressed; by CVC and *G* parity violating

X	$\pi^{\pm}$	$a_1^{\pm}(1260)$	$b_1^{\pm}(1235)$	$a_0^{\pm}$ (980)	$\rho^{\pm}$	η
m_X[MeV]	139.6	1230	1229.5	984.7	775.5	547.5
G	$-$	$-$	$+$	$-$	$+$	$+$
J^P	0^-	1^+	1^+	0^+	1^-	0^-
weak coupling	A	A	A	V	V	n.a.
FCC or *SCC*	*FCC*	*FCC*	*SCC*	*SCC*	*FCC*	n.a.
f_X[MeV]	131	238[20]	~0.6[20]	~1.6	210	

Punzi

- S/sqrt(B) – does not behave well for low numbers of S (prefers 0.1/0.01 over 10/2)
- S/sqrt(S+B) – depends on BR!