Studying CP Violation via Amplitude Analysis (ii)

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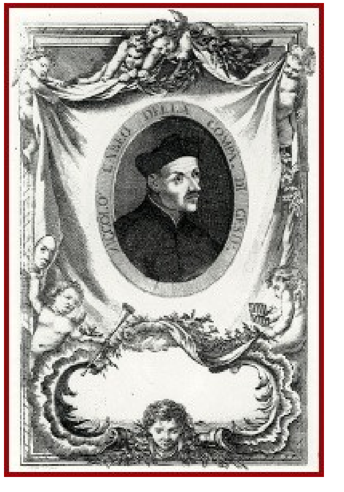
Hadronic spectroscopy

24th May 2012



Content of the lectures

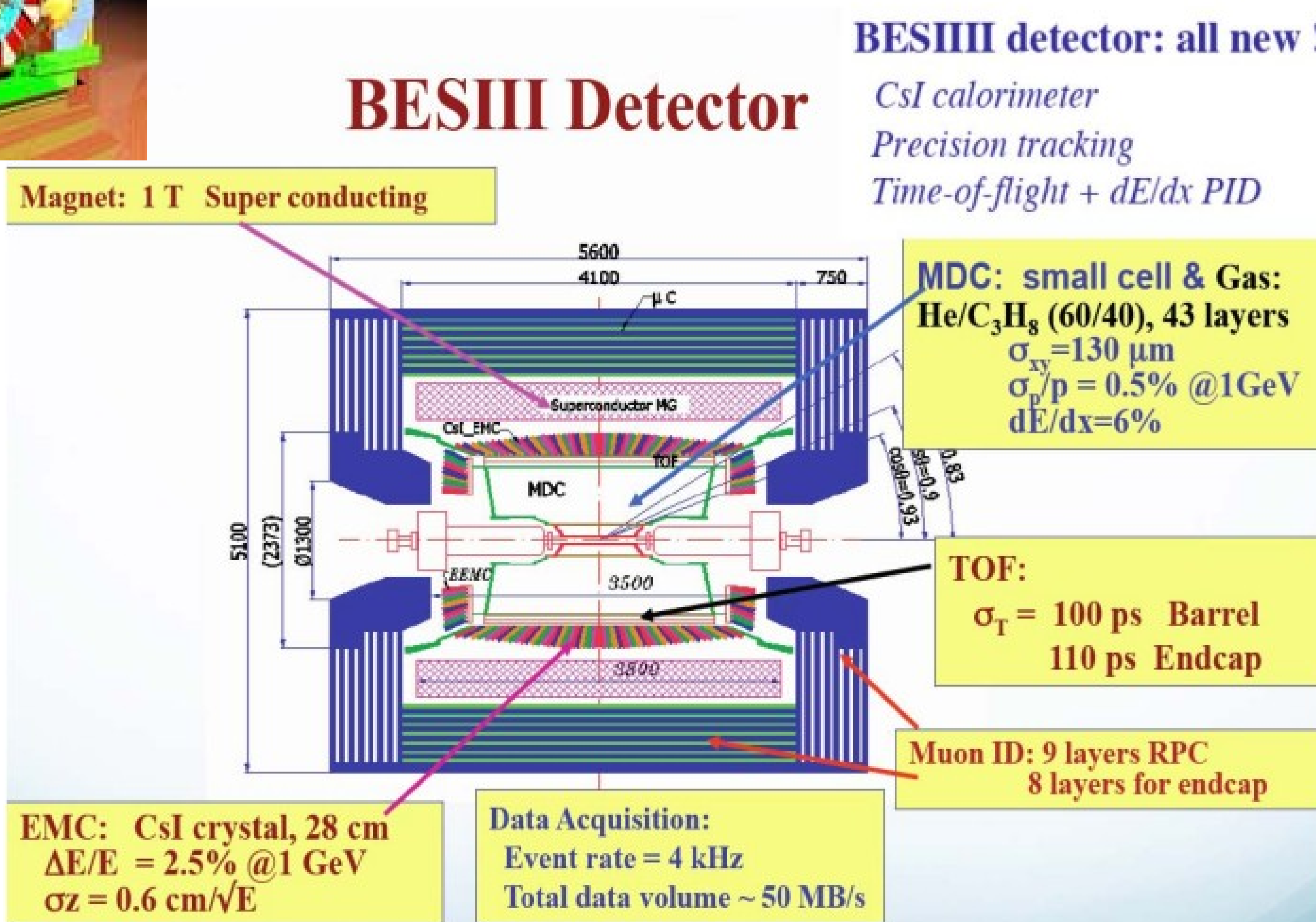
- Why do we believe that multibody hadronic decays of heavy flavours may provide a good laboratory to search for new sources of CP violation?

- Which decays in particular should we look at?

- What methods can we use to study them?

- What are the difficulties we encounter when trying to do the analysis?

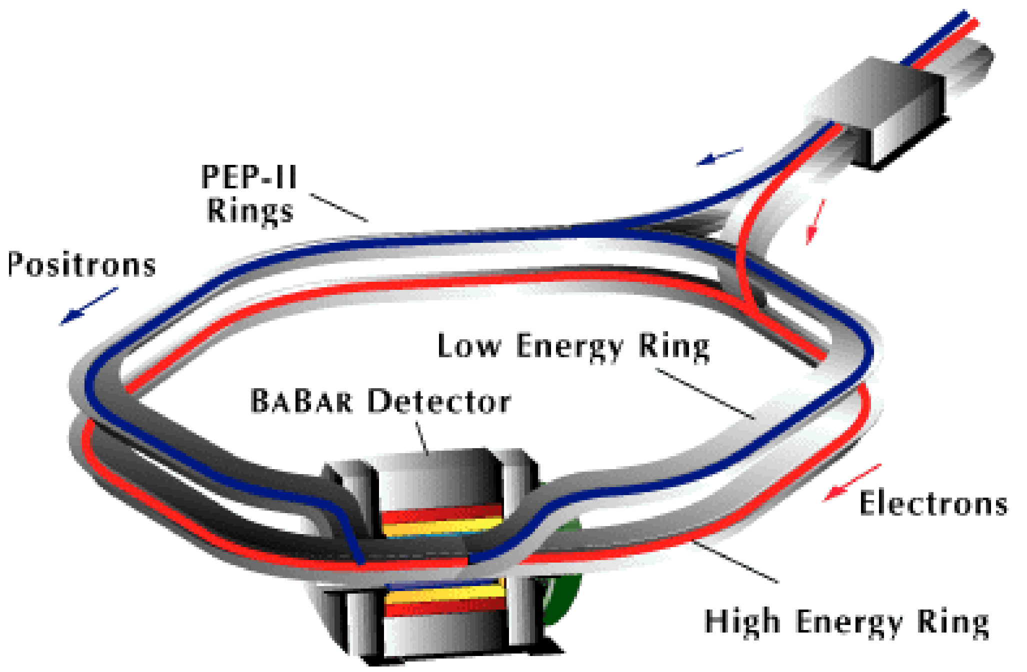
But first, let's look at some experiments



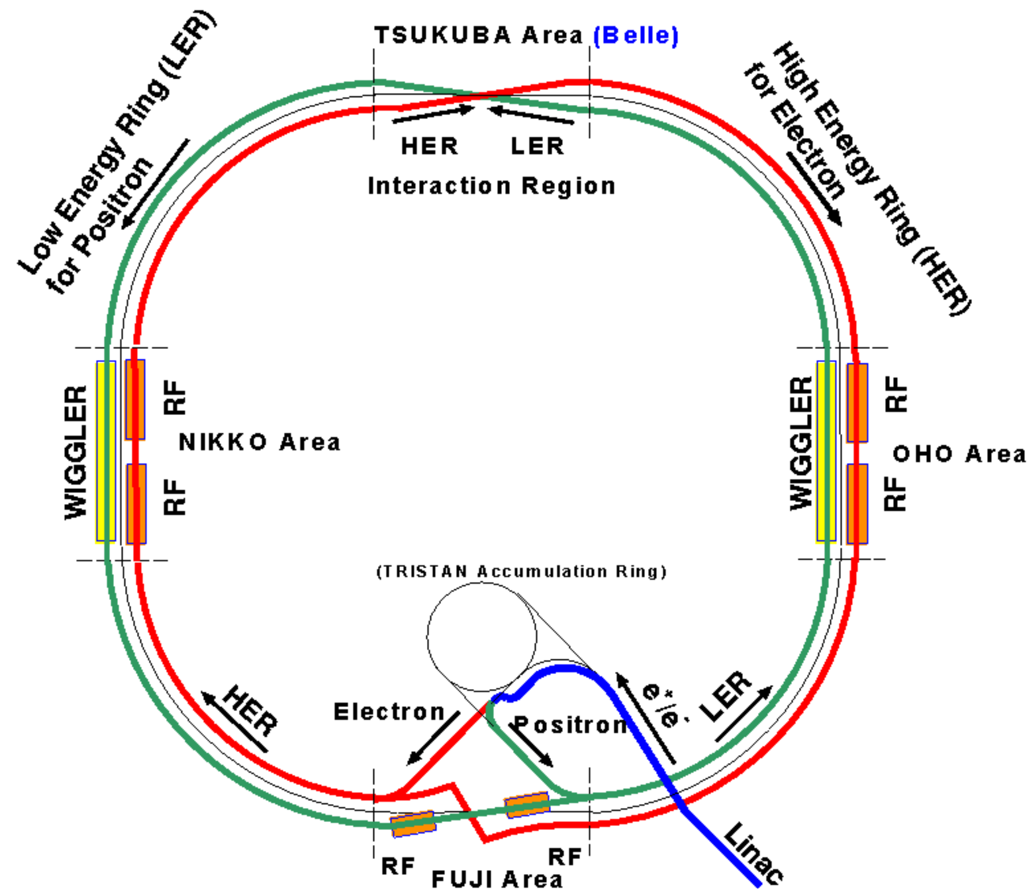
BESIII Detector
BESIII detector: all new !
CsI calorimeter
Precision tracking
Time-of-flight + dE/dx PID
Magnet: 1 T Super conducting
MDC: small cell & Gas:
He/C3H8 (60/40), 43 layers
σxy=130 μm
σp/p = 0.5% @1GeV
dE/dx=6%
TOF:
σT = 100 ps Barrel
110 ps Endcap
Muon ID: 9 layers RPC
8 layers for endcap
EMC: CsI crystal, 28 cm
ΔE/E = 2.5% @1 GeV
σz = 0.6 cm/√E
Data Acquisition:
Event rate = 4 kHz
Total data volume ~ 50 MB/s
5600
4100
750
μC
Superconductor MG
CsI_EMC
TOF
MDC
BEMC
3500
3800
5100
(2373)
Ø1300
cosθ=0.93
cosθ=0.9
0.83

The Asymmetric B Factories

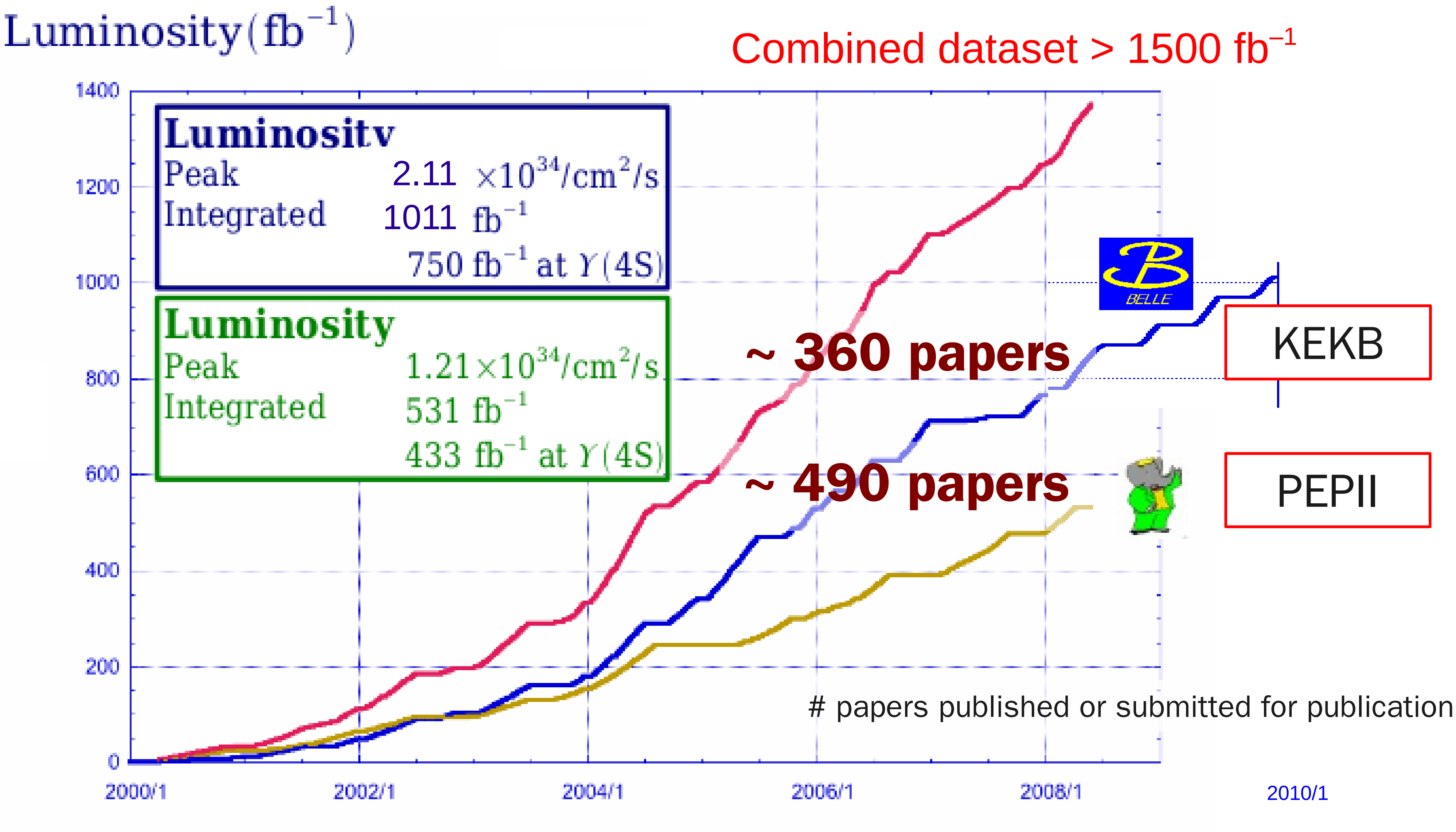
PEPII at SLAC
9.0 GeV e^- on 3.1 GeV e^+



KEKB at KEK
8.0 GeV e^- on 3.5 GeV e^+



B factories – World Record Luminosities

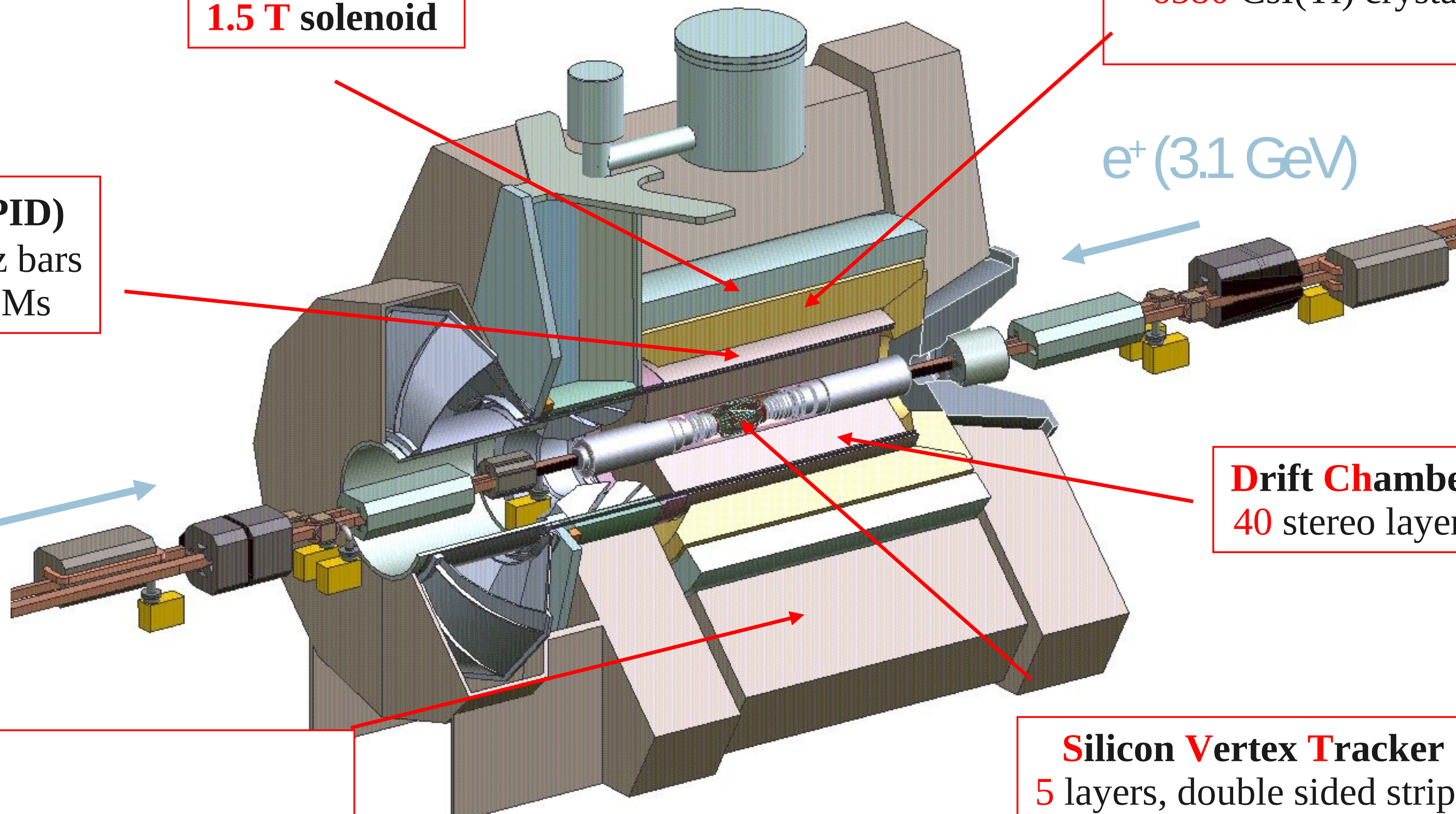


BaBar Detector

EMC
6580 CsI(Tl) crystals

1.5 T solenoid

DIRC (PID)
144 quartz bars
11000 PMs

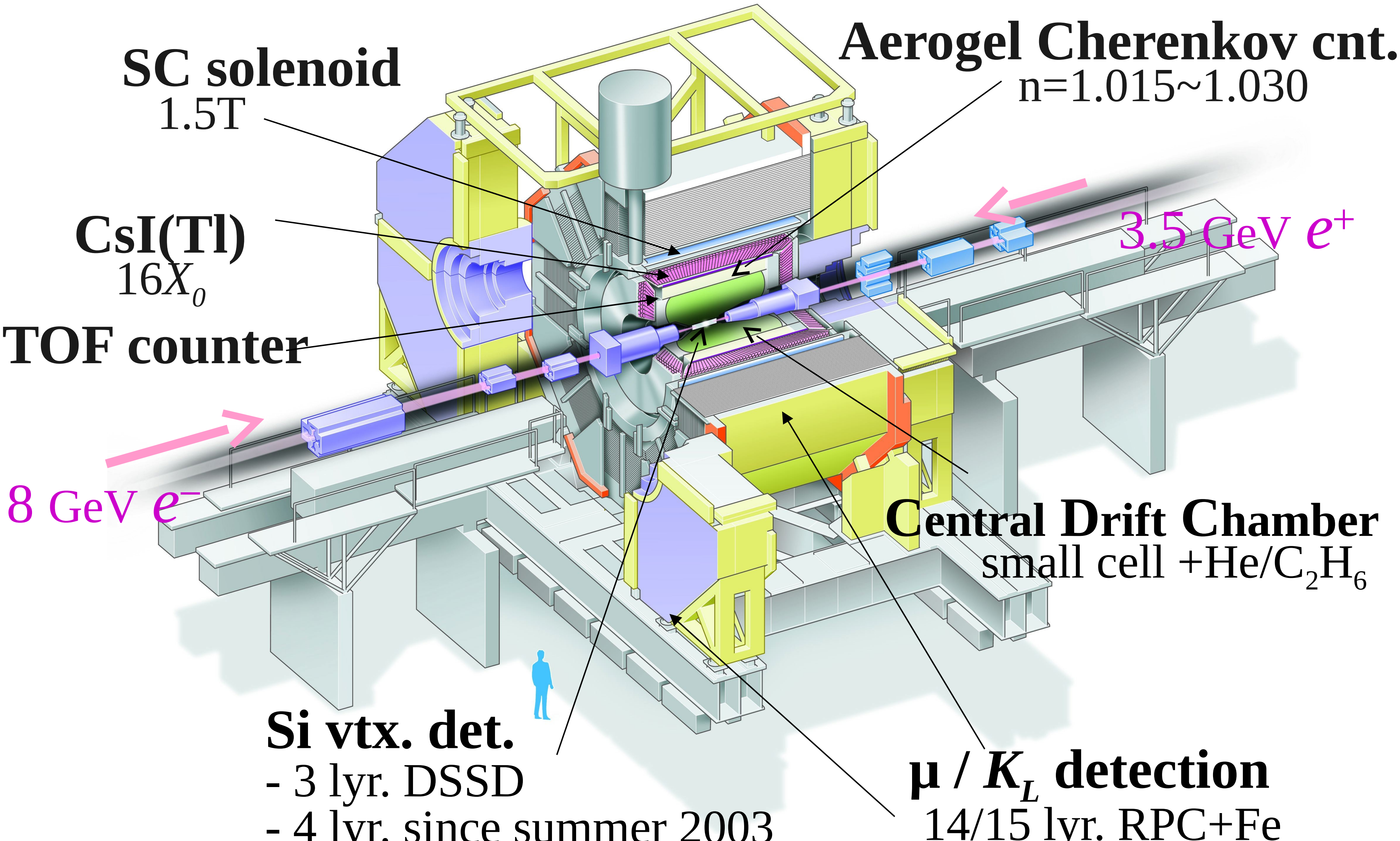


Drift Chamber
40 stereo layers

Silicon Vertex Tracker
5 layers, double sided strips

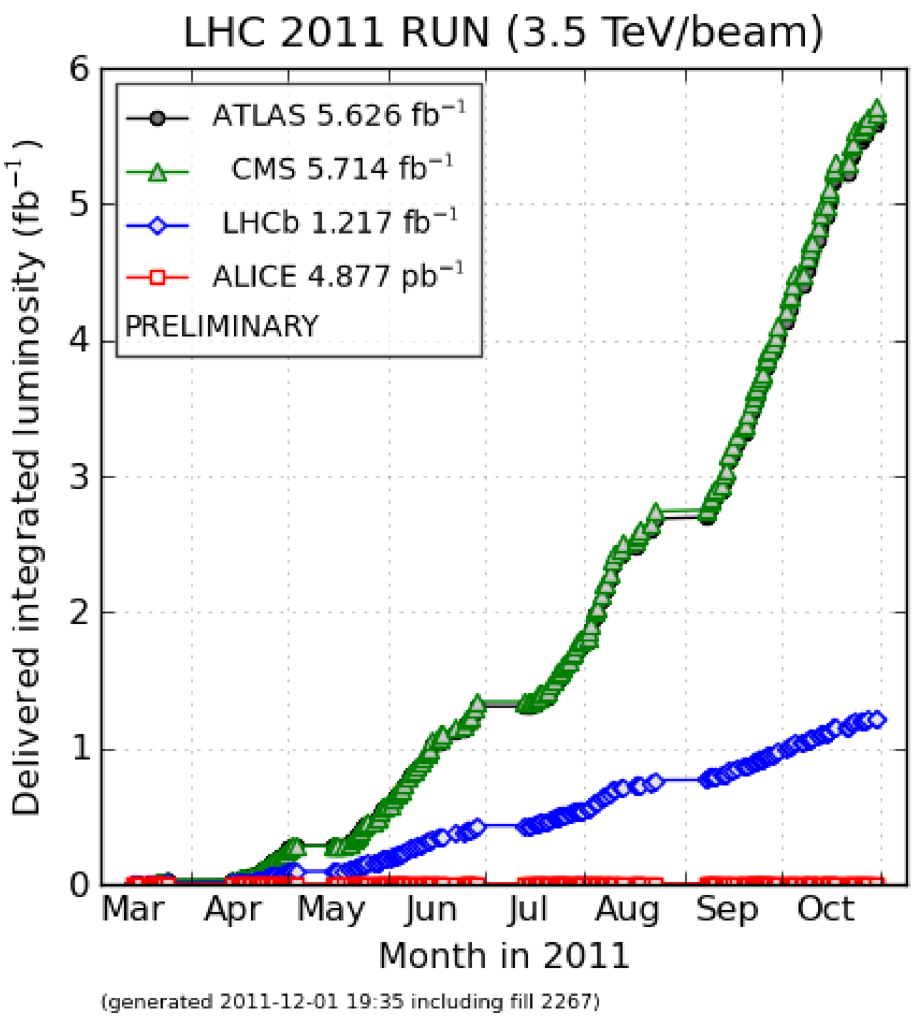
Instrumented Flux Return
iron / RPCs (muon / neutral hadrons)
2/6 replaced by LST in 2004
Rest of replacement in 2006

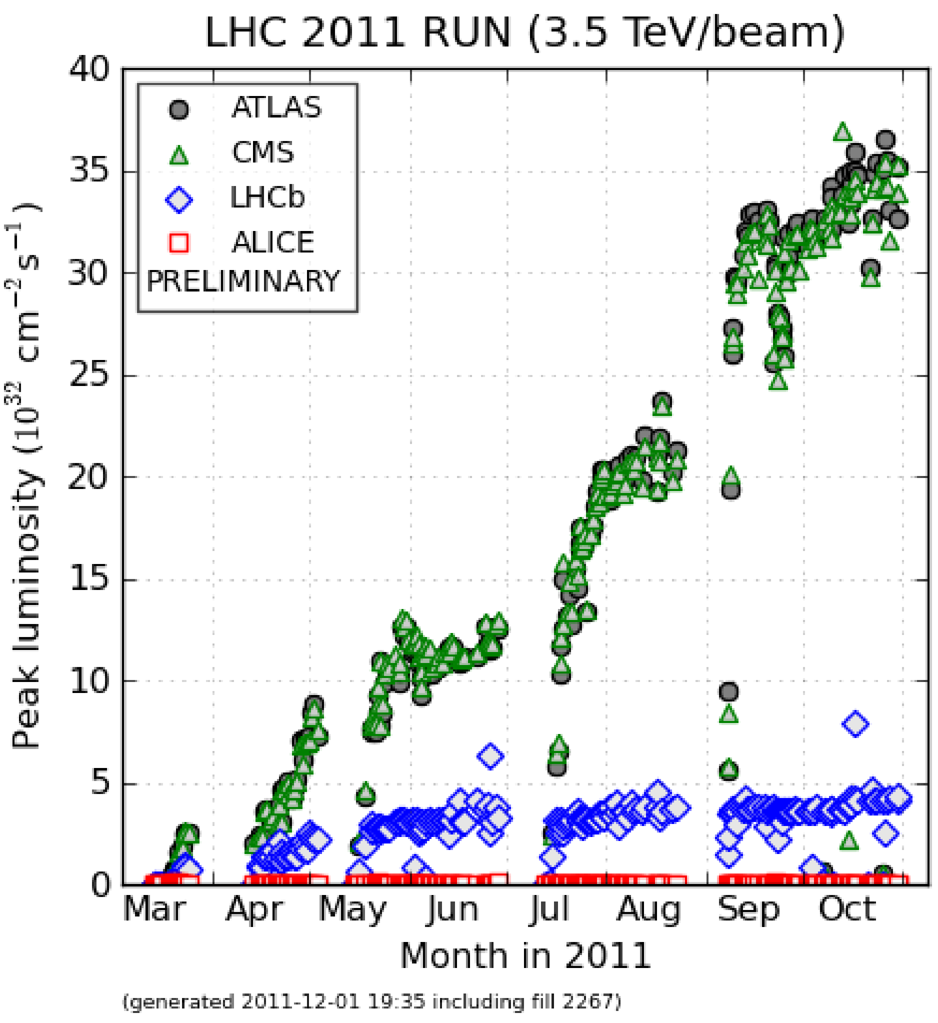
Belle Detector



The LHC

LHC performance 2011





LHCb design luminosity: 2 10^{32}/cm^2/s

What does $\int L\,dt$ = 1/fb mean?

- Measured cross-section, in LHCb acceptance

$$\sigma(pp \to b\bar{b}X) = (75.3 \pm 5.4 \pm 13.0)\ \mu b$$

PLB 694 (2010) 209

- So, number of $b\bar{b}$ pairs produced

$$10^{15} \times 75.3\ 10^{-6} \sim 10^{11}$$

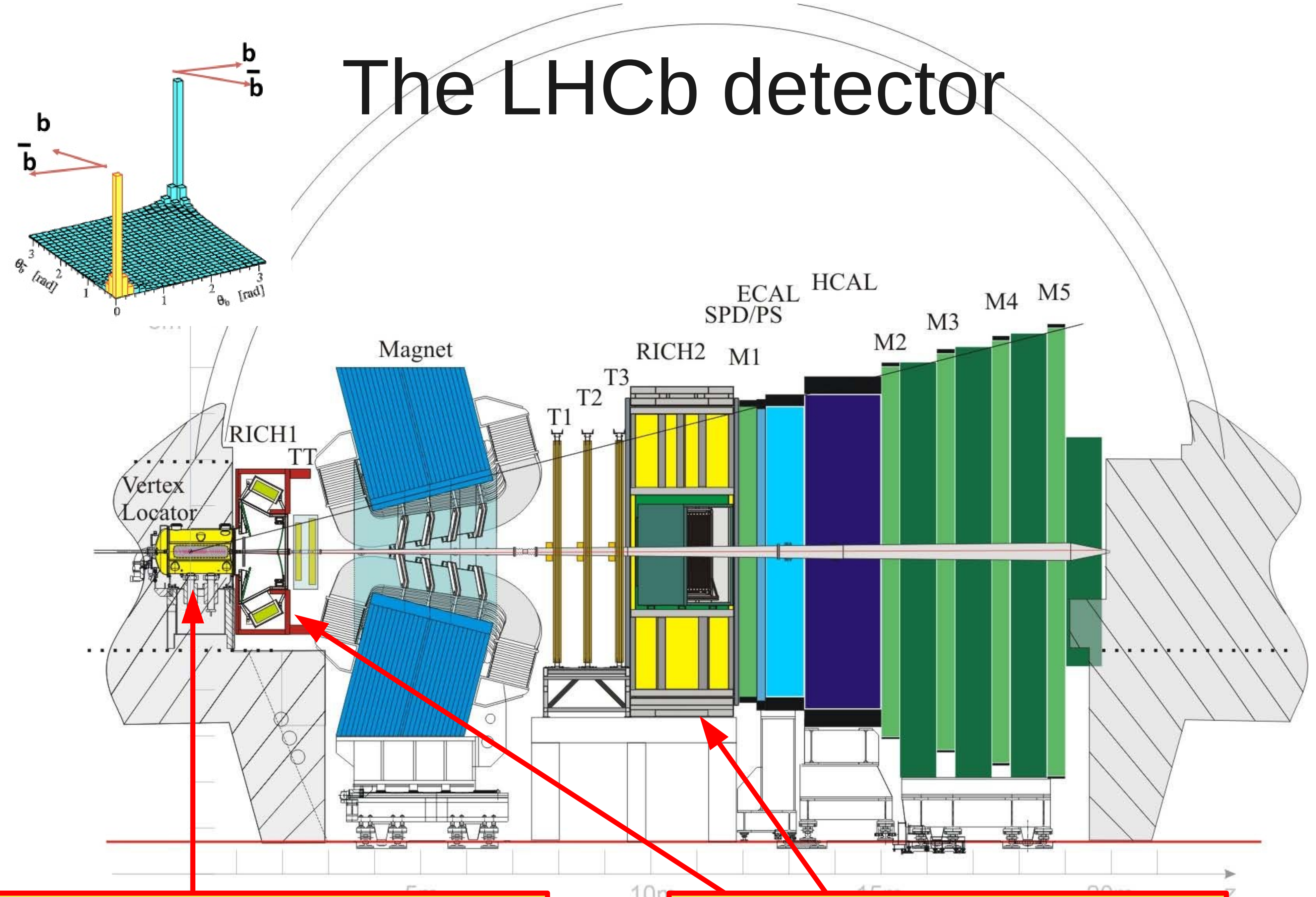
- Compare to combined data sample of e^+e^- “B factories” BaBar and Belle of ~ 10^9 $B\bar{B}$ pairs

for any channel where the (trigger, reconstruction, stripping, offline) efficiency is not too small, LHCb has world's largest data sample

- p.s.: for charm, $\sigma(pp \to c\bar{c}X) = (6.10 \pm 0.93)$ mb

LHCb-CONF-2010-013

The LHCb detector



Precision primary and secondary vertex measurements

Excellent K/π separation capability

Lepton vs. hadron colliders

- All these examples can be put into one of two categories
  - e^+e^- colliders (KLOE, CLEOc, BES, BaBar, Belle, etc.)
    - produce meson-antimeson pair in coherent state
  - hadron colliders (NA48, CDF, D0, LHCb, etc.)
    - produce hadrons from various mechanisms, such as gluon splitting
- What are relative advantages and disadvantages of the two approaches?
  - (More specific: in which do you expect the background to be lower?)

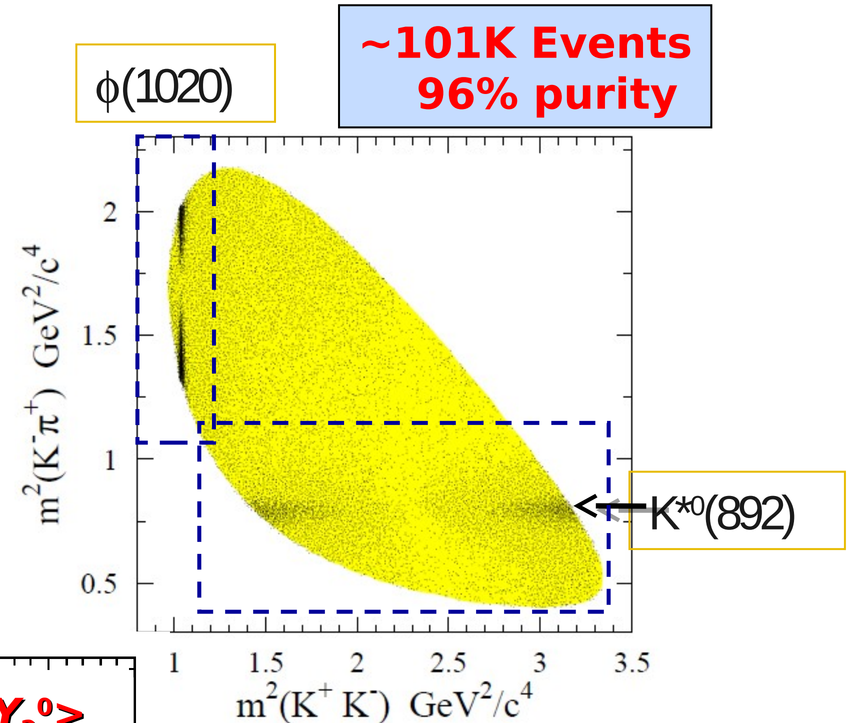
What methods can we use to study multibody hadronic decays of heavy flavours (and search for CP violation)?

Methods

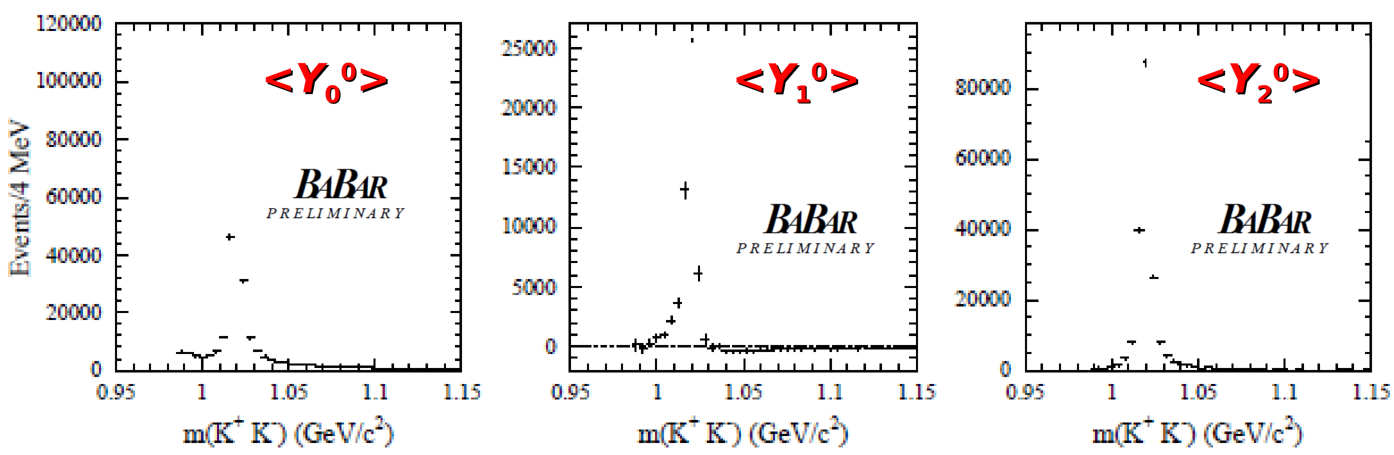
- Two-sample comparison tests
  - To ask: is there CP violation? Yes/No
  - (If yes, can extend to ask: where on the Dalitz plot does it occur?)
- Quantitative determinations of CP phases
  - Model independent approaches
  - Amplitude analyses
    - suffer from hard-to-quantify model dependence
    - improve by using better models …
    - … using data to provide insights into hadronic effects
    - example: partial wave analysis

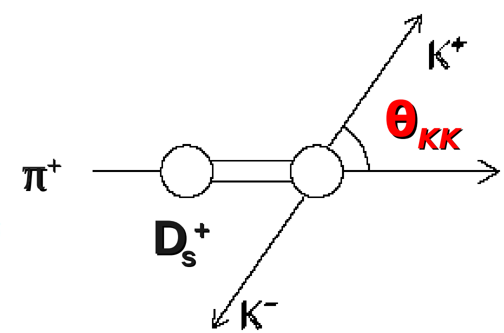
Example partial wave analysis: $D_s^+ \to K^+K^-\pi^+$ (BaBar)

Plot $m(K^+K^-)$, weighting events by factors $Y_L^0(\cos\theta_{KK})/\varepsilon$ to obtain "moments $\langle Y_L^0(m)\rangle$"



$$
\begin{aligned}
\sqrt{4\pi}\langle Y_0^0\rangle &= |S|^2 + |P|^2 \\
\sqrt{4\pi}\langle Y_2^0\rangle &= \frac{2}{\sqrt{5}}|P|^2, \\
\sqrt{4\pi}\langle Y_1^0\rangle &= 2|S||P|\cos\phi_{SP}
\end{aligned}
$$

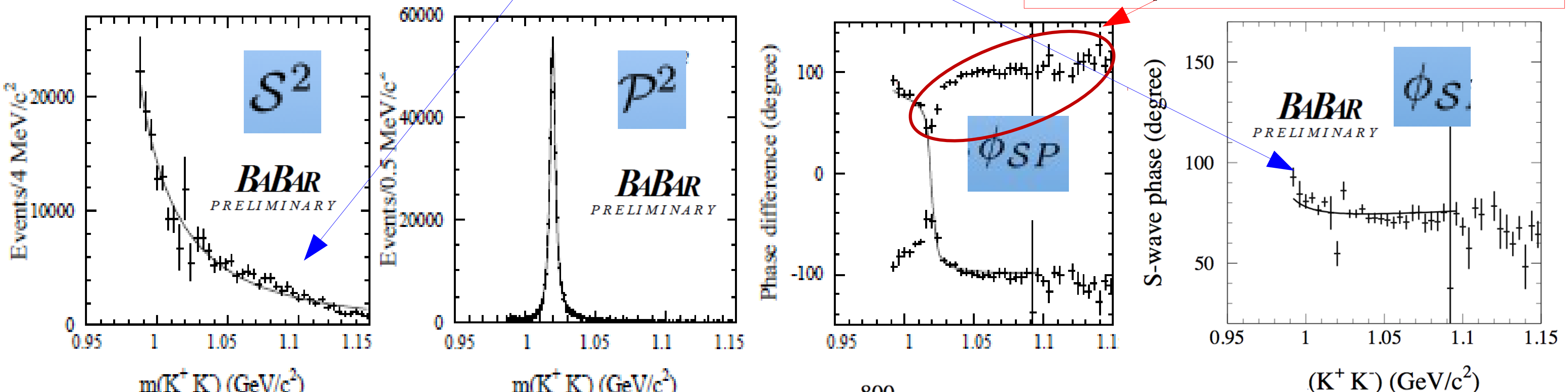




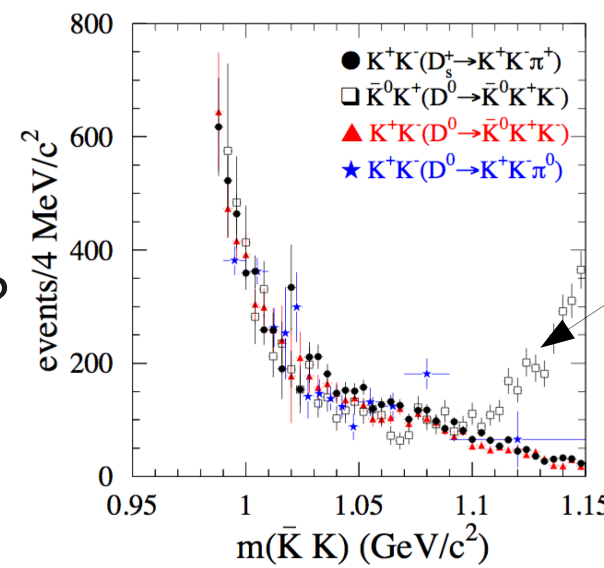
Example partial wave analysis: $D_s^+ \to K^+K^-\pi^+$ (BaBar)

(Approximately) model-independent information on the KK S-wave magnitude and phase

Ambiguity in φ_{SP} resolved by knowledge of $\varphi(1020)$ phase variation



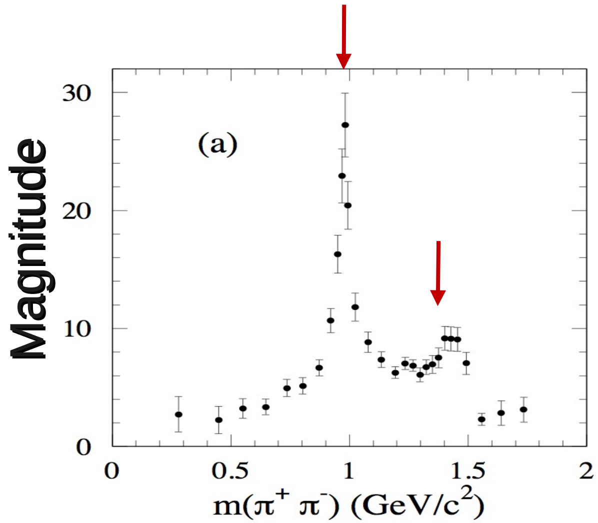
KK S-wave seems process independent?

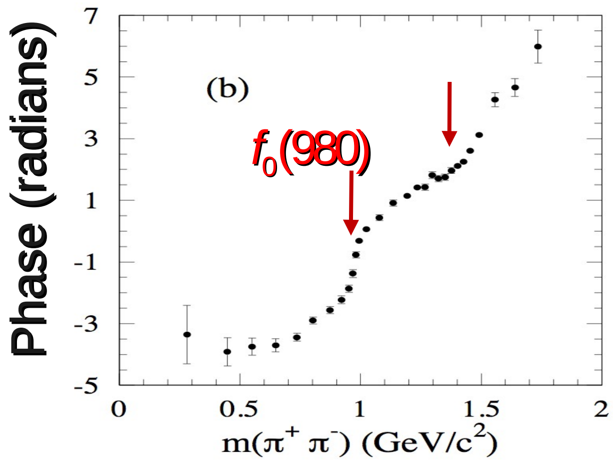


From K^+K^- cross channel

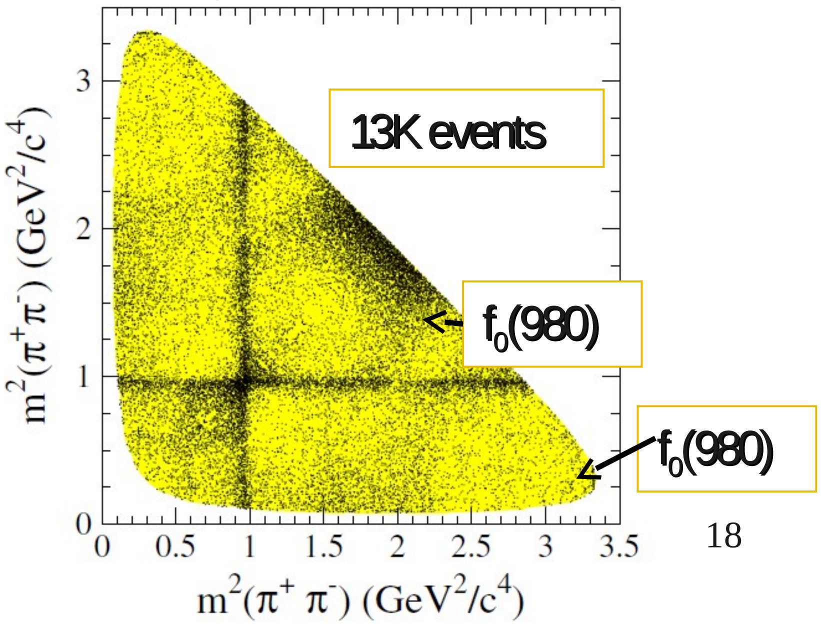
Quasi-model-independent partial wave analysis

- Pioneered by E791 (B.Meadows) in $D^+ \rightarrow K^- \pi^+ \pi^+$
- Describe S-wave by complex spline (many free parameters)
- Example: $D_s^+ \rightarrow \pi^- \pi^+ \pi^+$ from BaBar

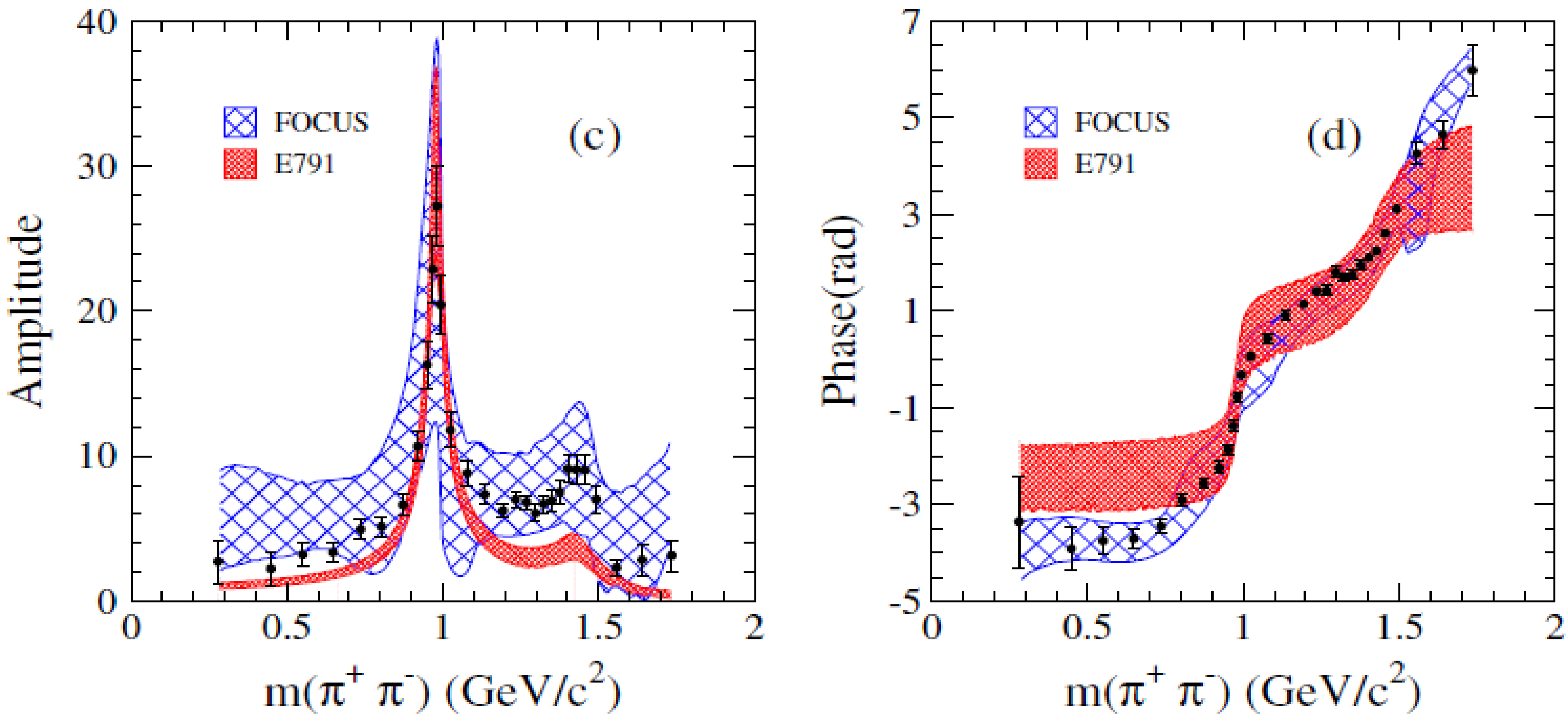




Symmetrized Dalitz plot

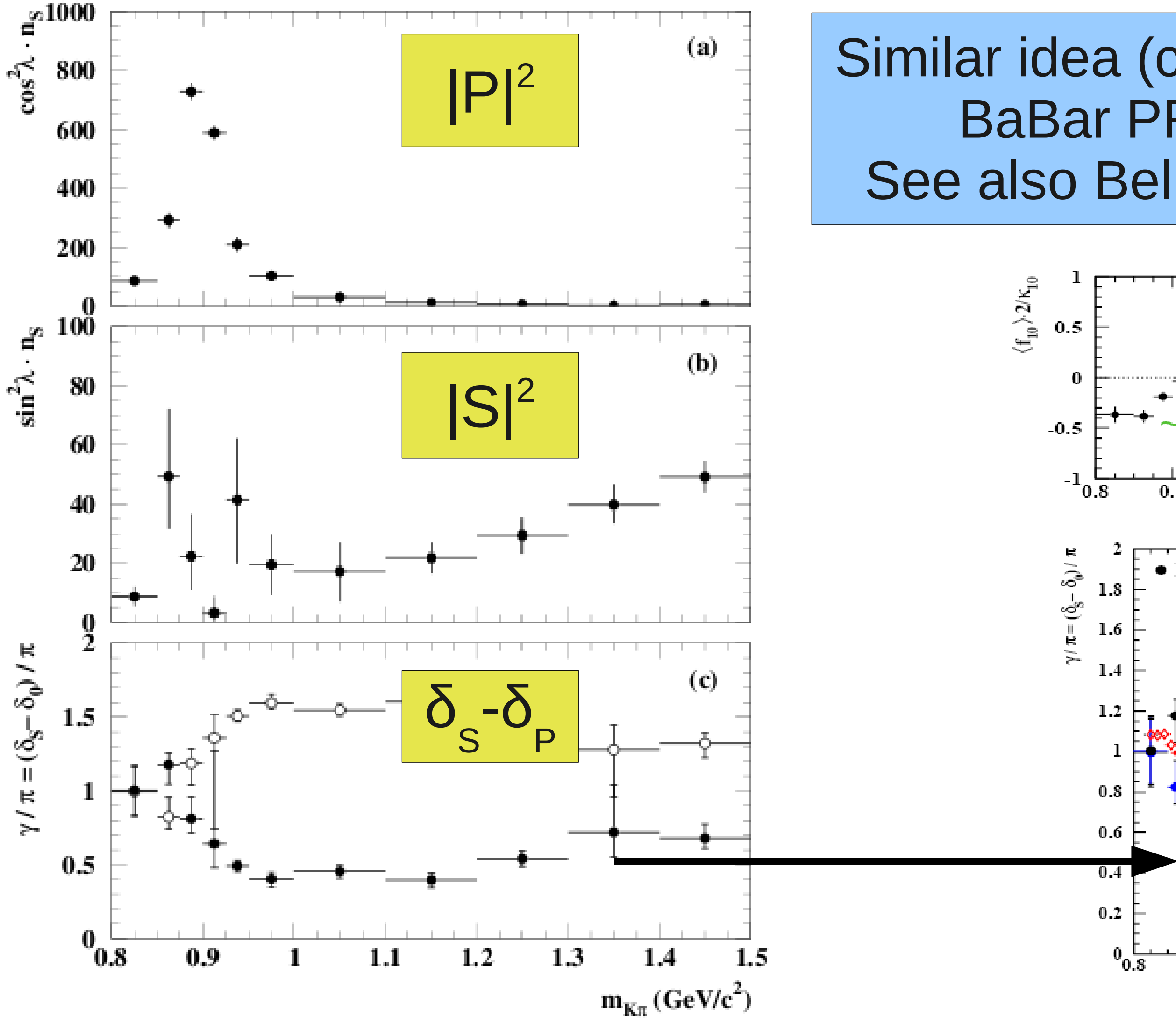


ππ S-wave comparison

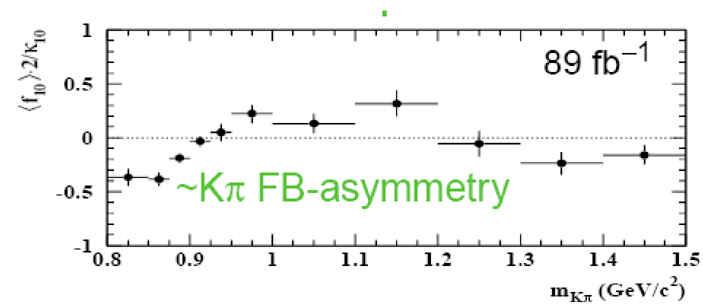


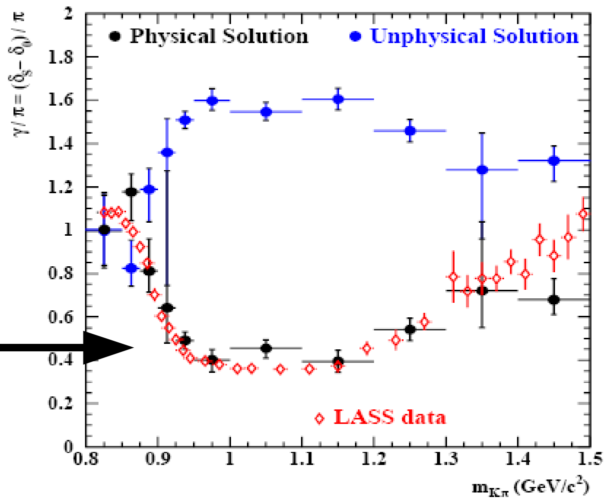
Data points from BaBar

$B \to J/\psi\ K\pi$



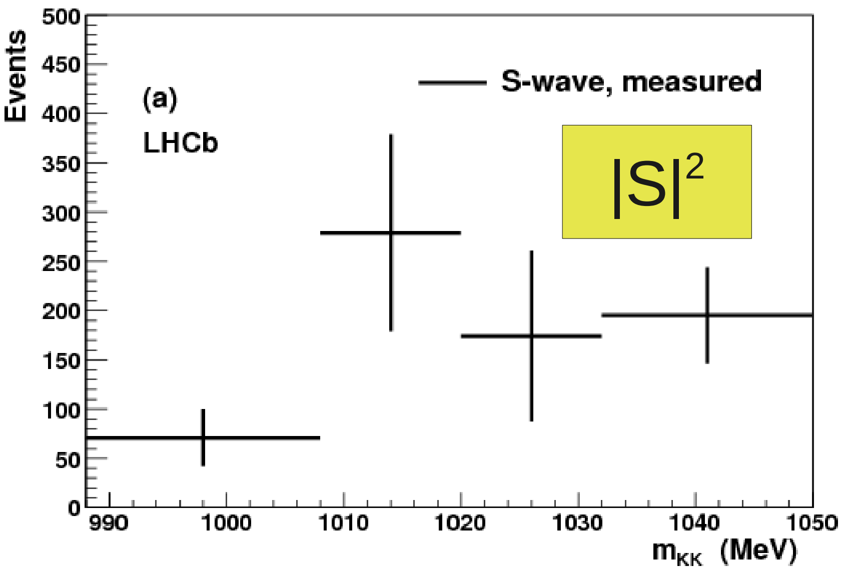
Similar idea (complicated by spin of J/ψ)
BaBar PRD 71 (2005) 032005
See also Belle PRL 95 (2005) 091601



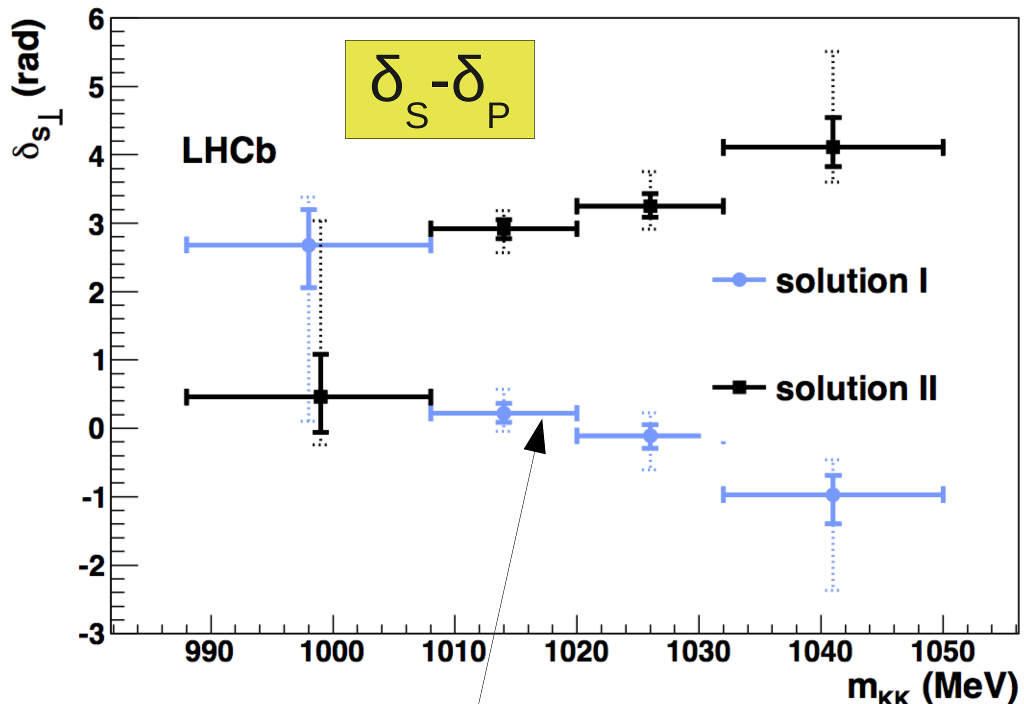


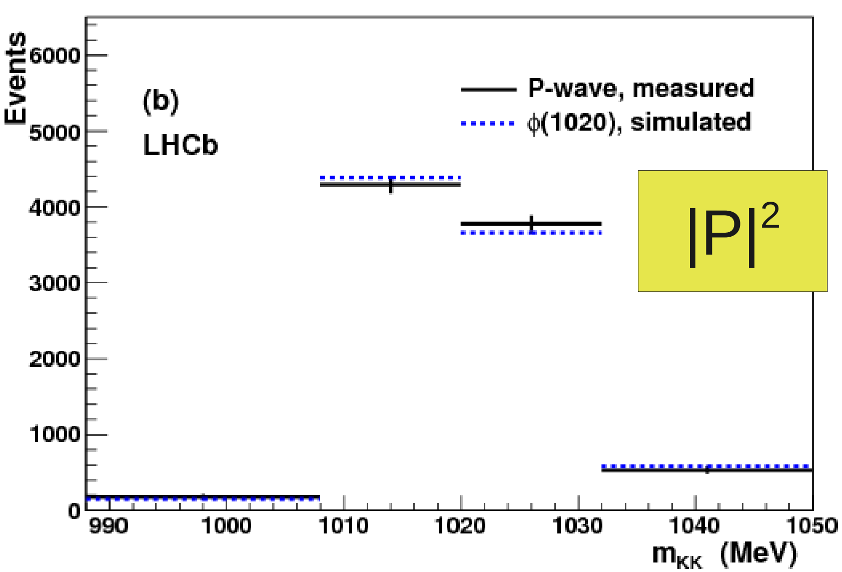
Essential input to unambiguous measurement of cos(2β) using $B \to J/\psi\ K_S \pi^0$

$B_s \to J/\psi$ KK



Similar idea (complicated by spin of J/ψ)
LHCb arXiv:1202.4717

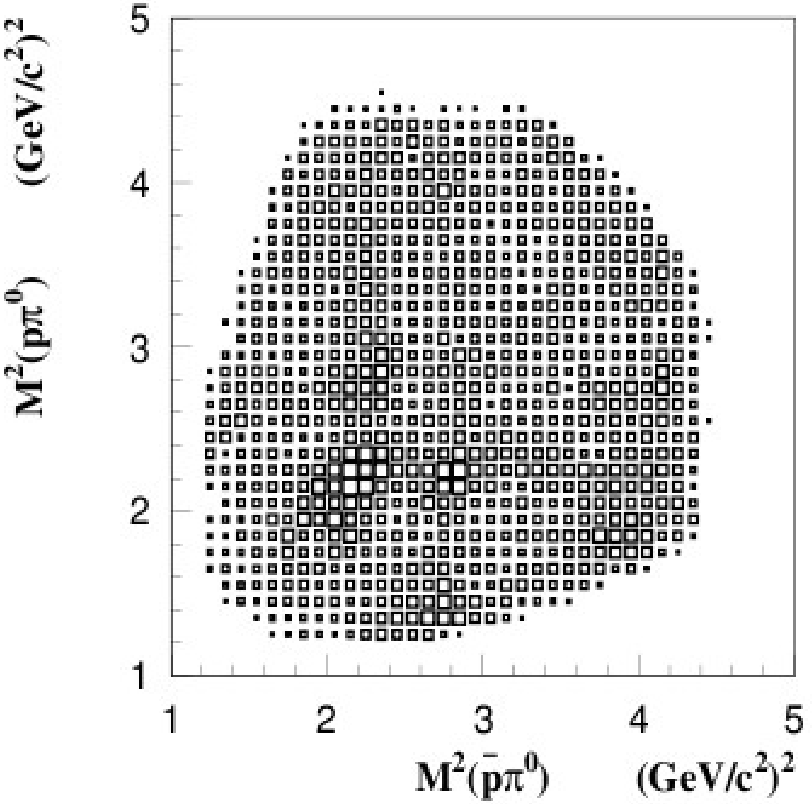


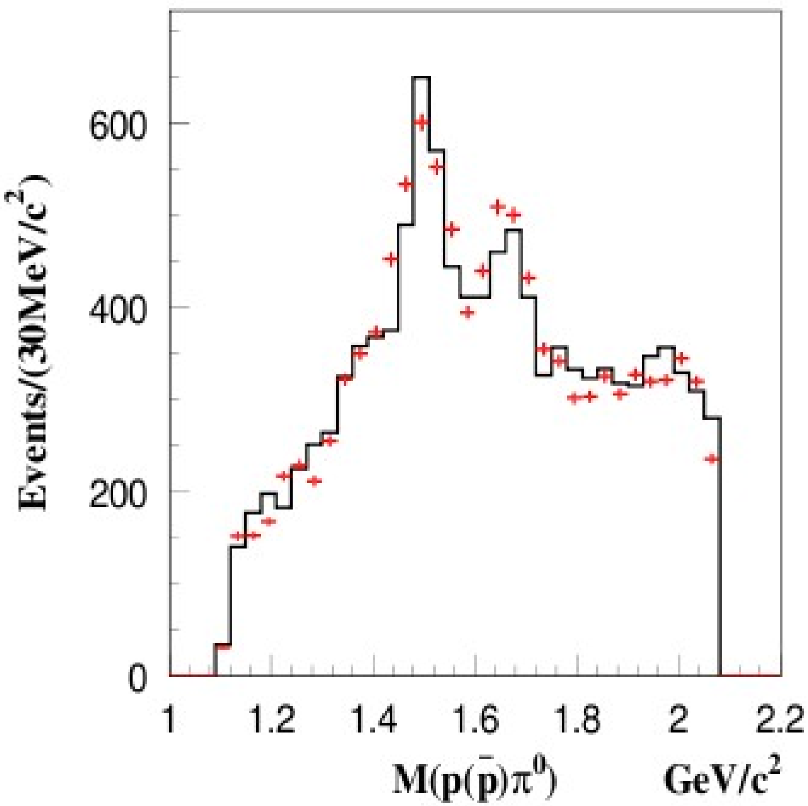


Physical solution corresponds to ΔΓs>0 and value of φs consistent with SM

“Partial wave analysis of $J/\psi \to p\bar{p}\pi^0$” at BESII

PRD 80 (2009) 052004





An important and interesting amplitude analysis … but not a partial wave analysis in the (quasi- model-independent) sense that I have been using

What are the difficulties we encounter when trying to do the analysis?

Difficulties, difficulties ...

- Backgrounds
- Efficiency
- Misreconstruction & resolution
- Speed
- Parametrisations and conventions
- Goodness of fit
- Model dependence

Backgrounds

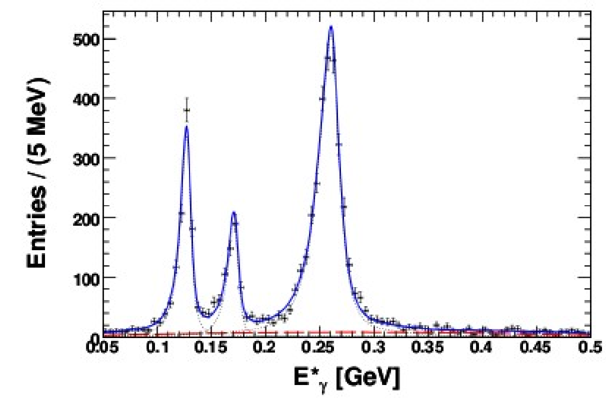
- Do you expect the background to be lower in lepton or hadron colliders?

Backgrounds

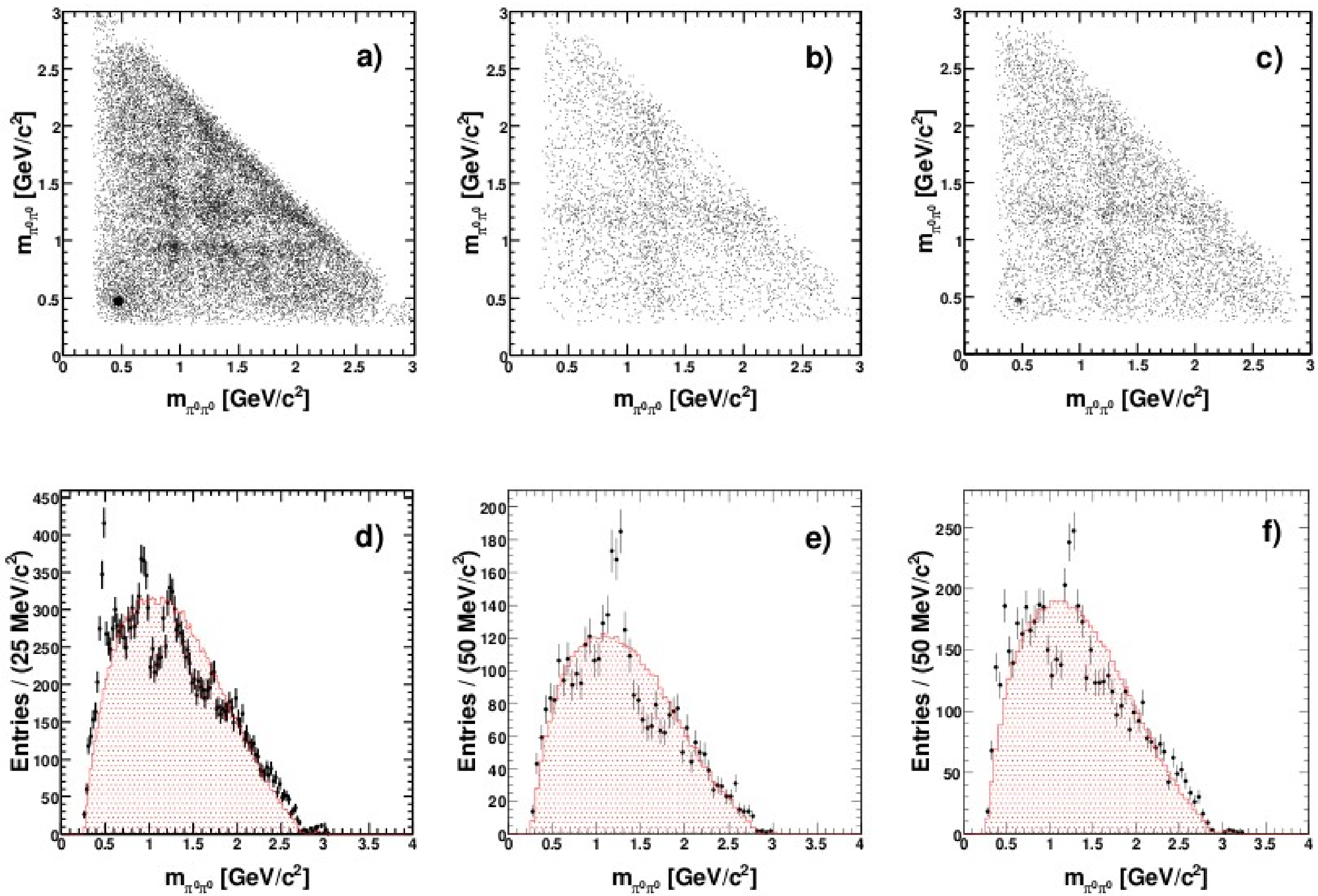
- Do you expect the background to be lower in lepton or hadron colliders?
  - It depends (of course …)
  - Overall multiplicity much lower in e^+e^- collisions
    - very low backgrounds if you reconstruct everything in the event
    - but if signal is, e.g., B meson from Υ(4S) decay, still have background from “the rest of the event”
  - Particles produced in hadron collisions have high momenta
    - can efficiently reduce background using variables related to flight distance and transverse momenta
    - extreme example: charged kaon beams

$\psi(2S) \rightarrow \gamma\chi_{cJ} \rightarrow \gamma(4\pi^0)$ at BESIII

PRD 83 (2011) 012006



χ_{c0} χ_{c1} χ_{c2}

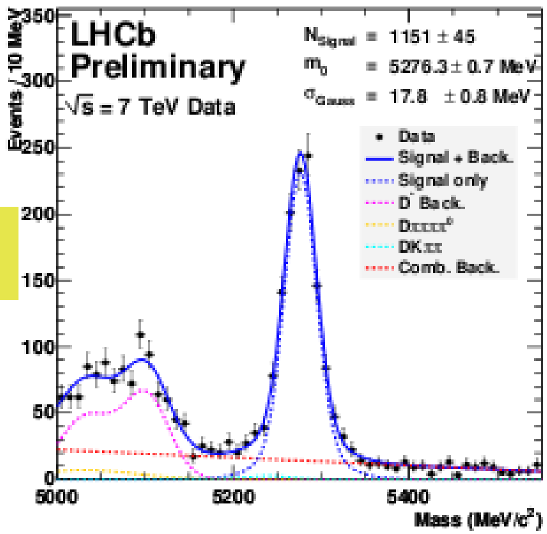


N.B. **Not** Dalitz plots!

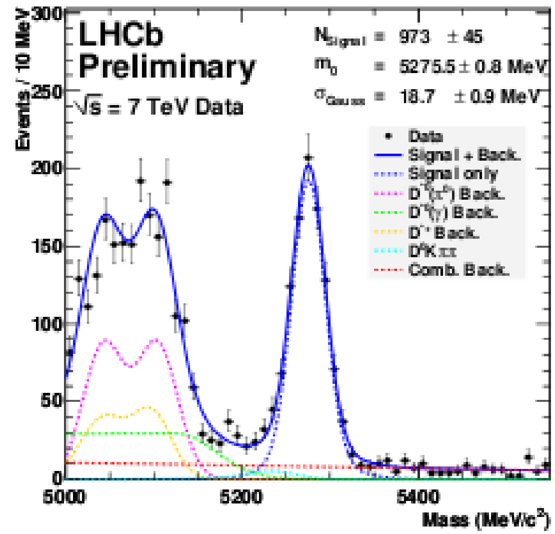
$X_b \rightarrow X_c 3\pi$ at LHCb

PRD 84 (2011) 092001

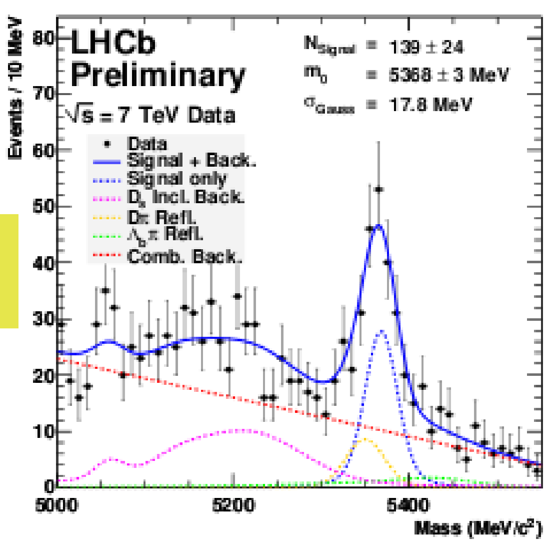
$D^+(3\pi)^-$



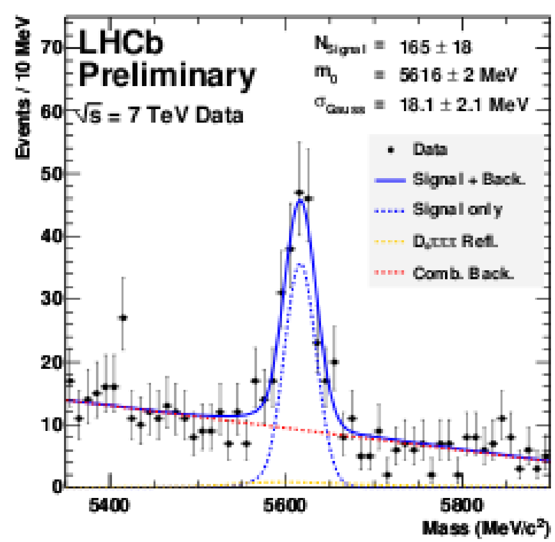
$D^0(3\pi)^-$



$D_s^+(3\pi)^-$

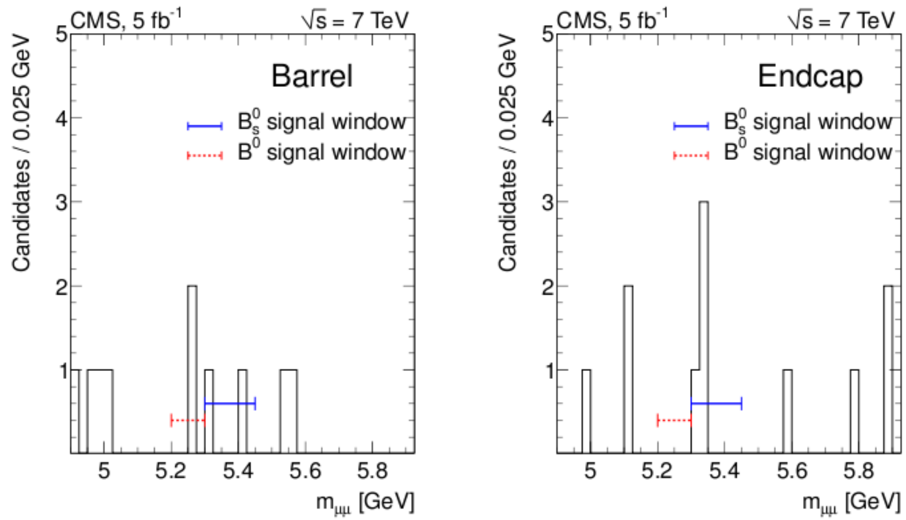


$\Lambda_c^+(3\pi)^-$

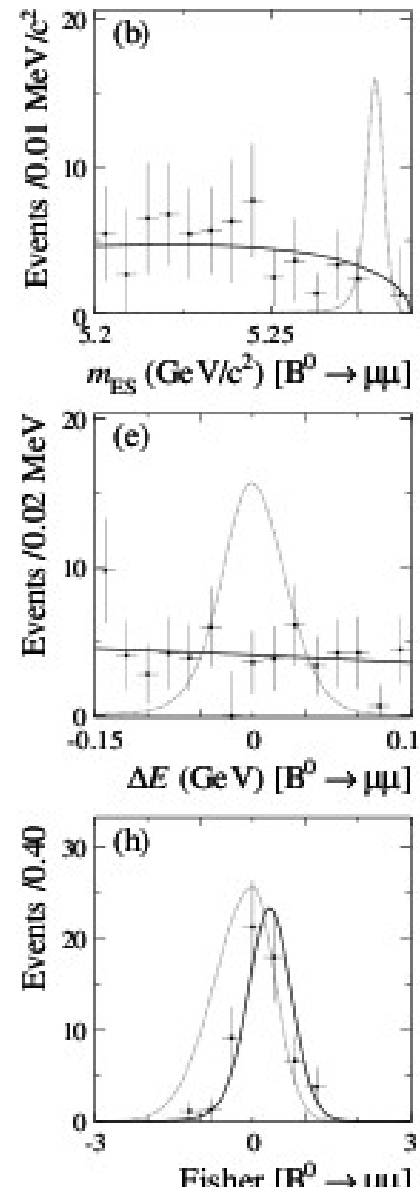


B → $\mu^+\mu^-$ comparison

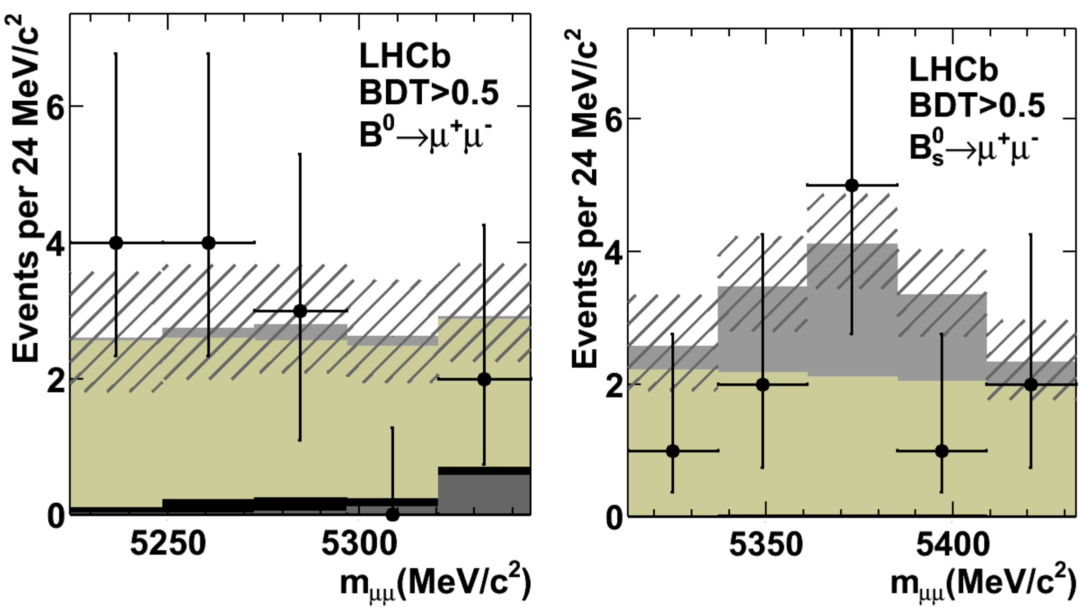
CMS JHEP 04 (2012) 033



BaBar PRD 77 (2008) 032007



LHCb arXiv:1203.4493



Maximum likelihood fit

$$L = \prod_{i=1}^{N} P_i$$

likelihood can also be "extended" to include Poisson probability to observe N events

$$-2\ln L = -2\sum_{i=1}^{N} \ln(P_i)$$

$$P_i = P_{i,sig} + P_{i,bkg}$$

need to obtain background distributions and to known background fraction (or event-by-event background probability)

$$P_{i,sig} = P_{i,phys} * R_{det}$$

convolution with detector response: includes efficiency and resolution

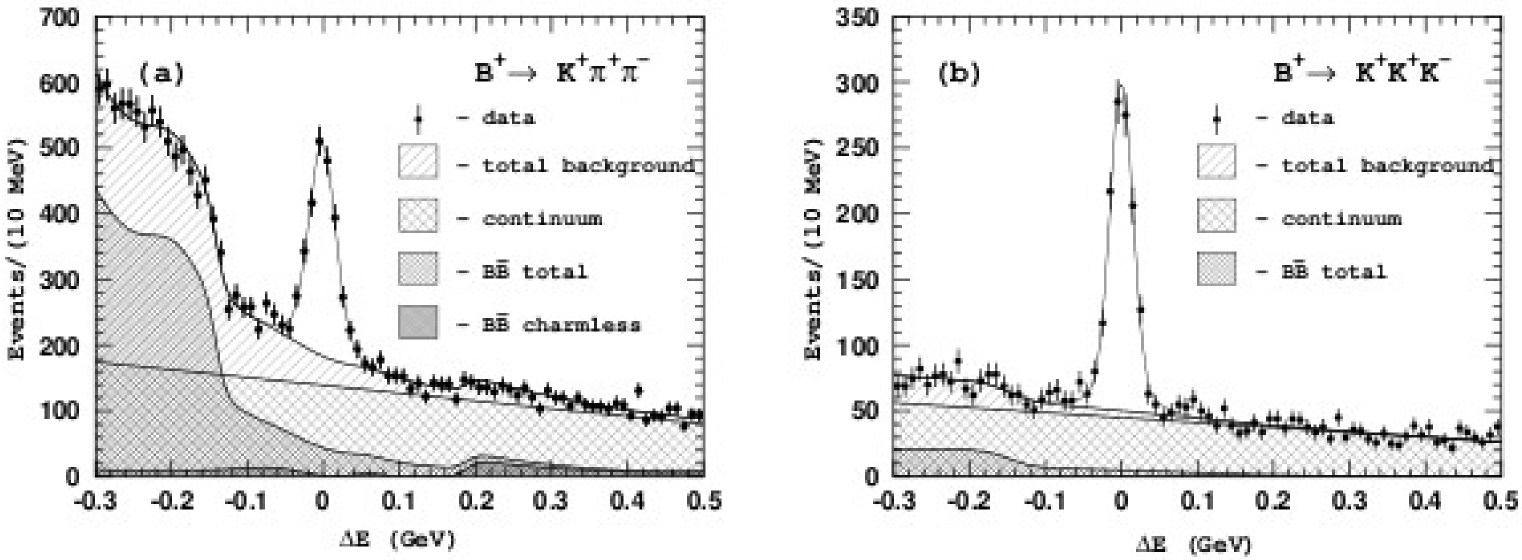
$P_{i,phys}$ contains the physics …
but most be coded in a way that allows reliable determination of the model parameters

In the case of a binned fit to data, sum over events is replaced by sum over bins

Background fractions and distributions

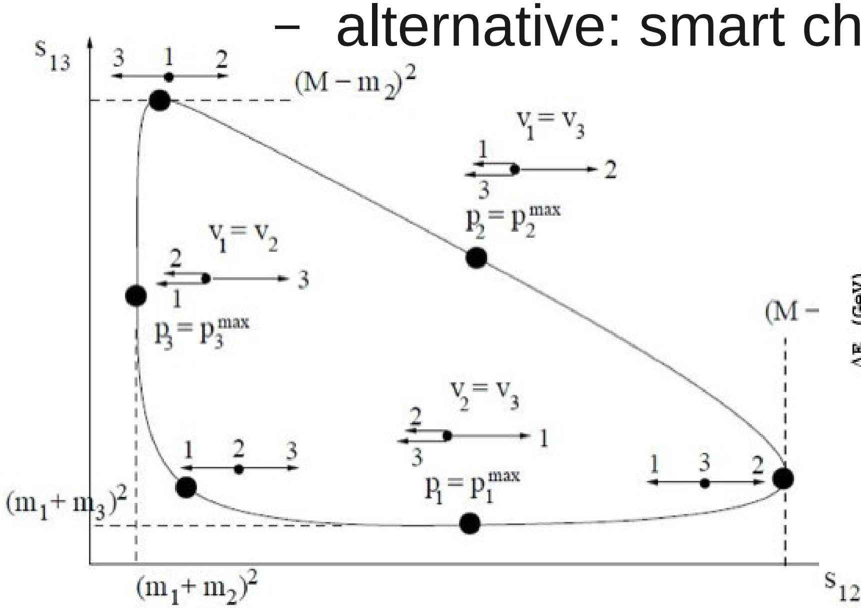
- It is usually possible to determine the background fraction by fitting some kinematic variable (e.g. invariant mass)
  - Can be done prior to, or simultaneously with, the fit to the Dalitz plot
- The background distribution can then be studied from sidebands of this variable
  - Care needed: background composition may be different in the signal and sideband regions

Belle PRD71 (2005) 092003

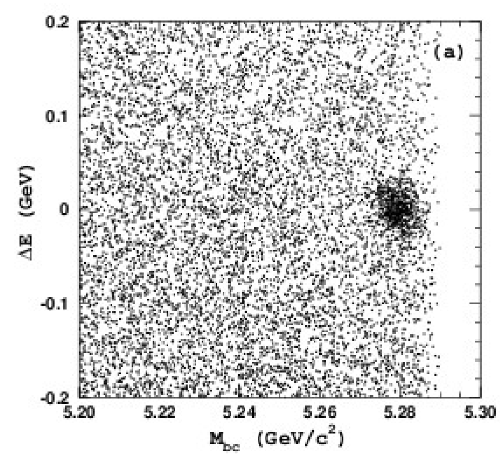


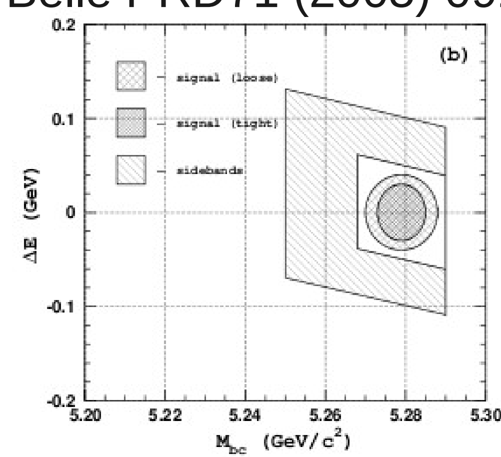
Background distribution issues

- Boundary of Dalitz plot depends on 3-body invariant mass
  - To have a unique DP, and to improve resolution for substructure, apply 3-body mass constraint
  - This procedure distorts the background shape
    - noticeable if narrow resonances are present in the sideband
    - can be alleviated by averaging upper and lower sidebands (not always possible)
    - alternative: smart choice of sidebands (not always possible)



Belle PRD71 (2005) 092003

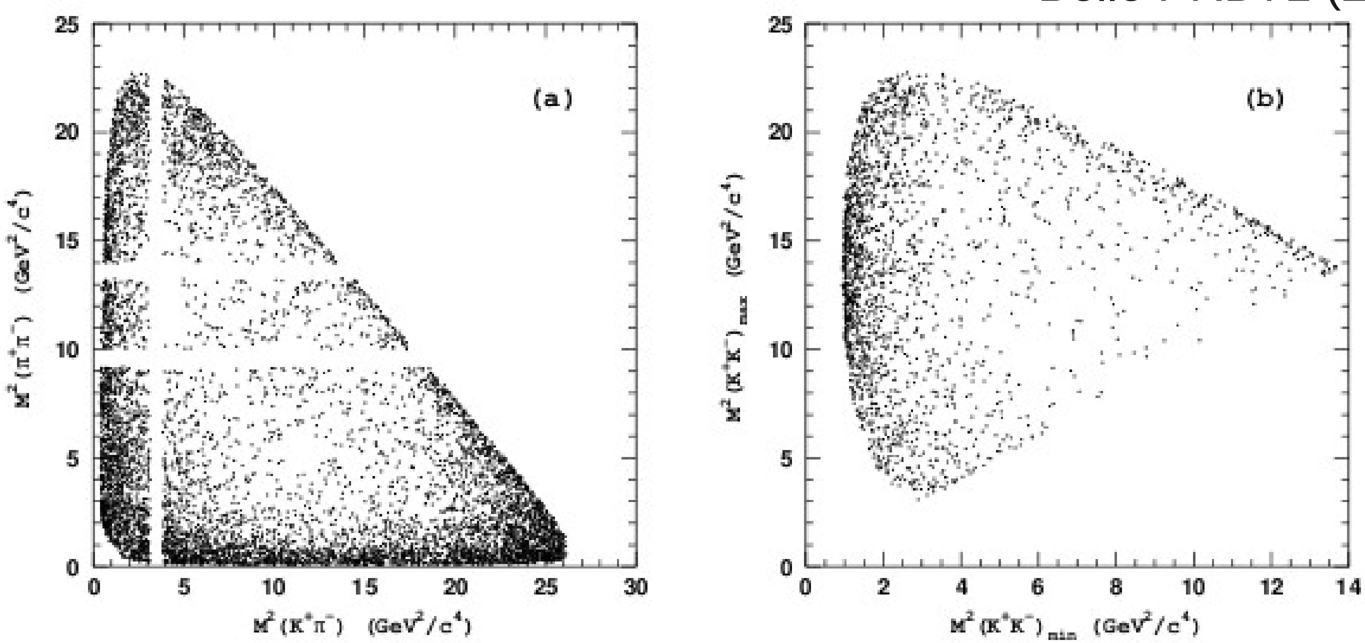




Background distribution issues

- In a binned fit, the background can be subtracted
- In an unbinned fit, the background PDF must be described, either
  - parametrically (usually some smooth function plus incoherent sum of narrow states)

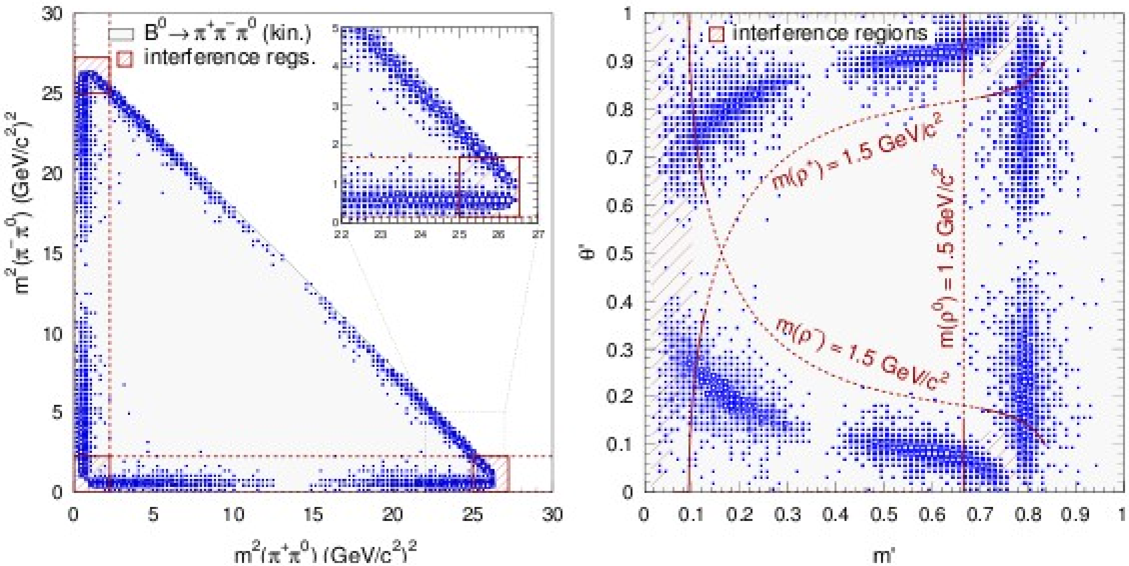
Belle PRD71 (2005) 092003



Background distribution issues

- In a binned fit, the background can be subtracted
- In an unbinned fit, the background PDF must be described, either
  - nonparametrically (usually as a histogram)
    - since background tends to cluster near DP boundaries, advantageous to use "square Dalitz plot"

BaBar PRD 76 (2007) 012004

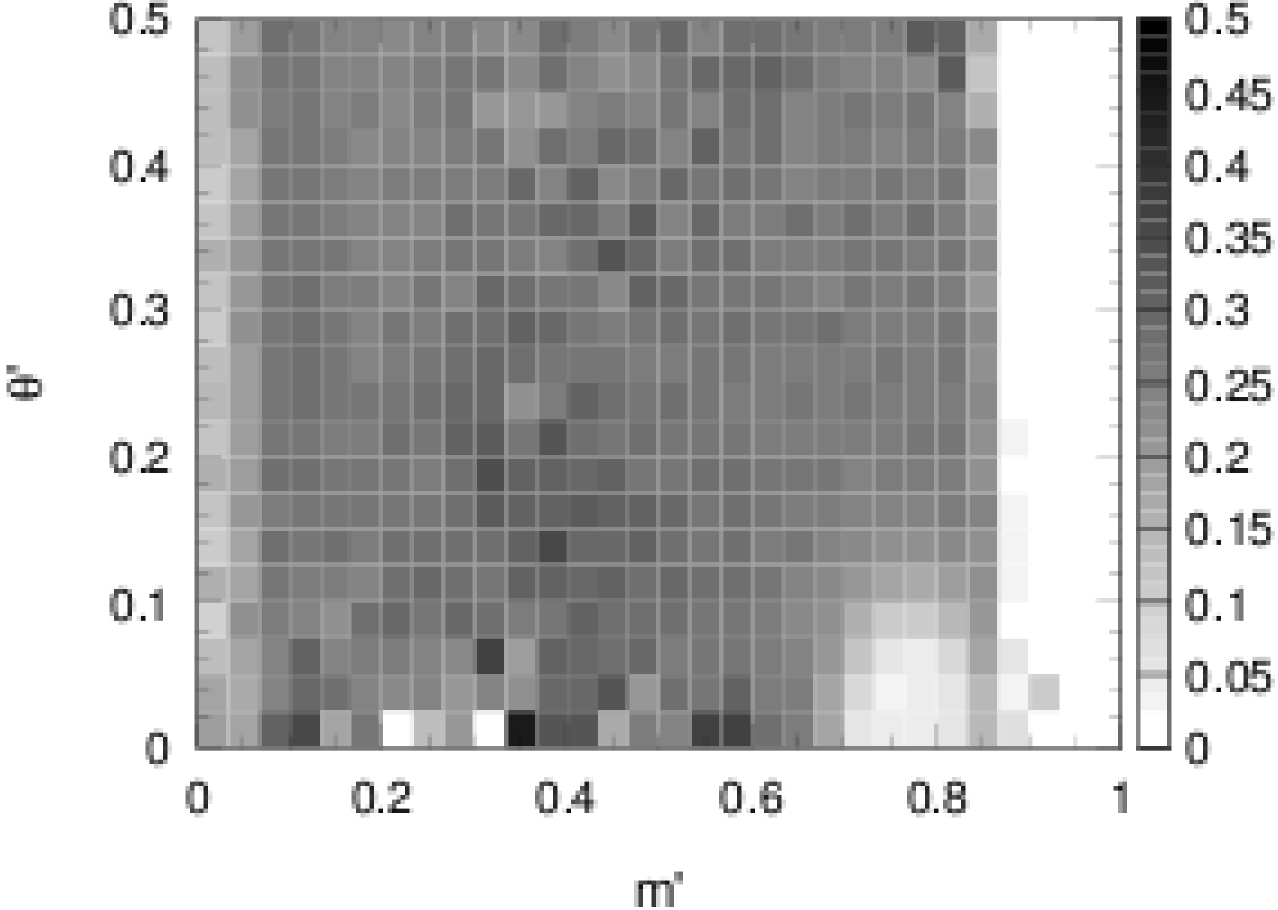


Detector response – efficiency

- Key point:
  - If the efficiency is uniform across the phase-space, we can ignore it in the maximum likelihood fit
- Efficiency non-uniformity must be accounted for
  - Choose selection variables to minimise effect
  - Determine residual variation from Monte Carlo simulation (validated/corrected using data where possible)
  - Can either
    - explicitly correct for efficiency (event-by-event)
      - usually implemented as a histogram (using square DP or otherwise)
    - determine overall effect from MC simulation with same model parameters
      - only viable approach for high-dimensional problems

Example of efficiency variation

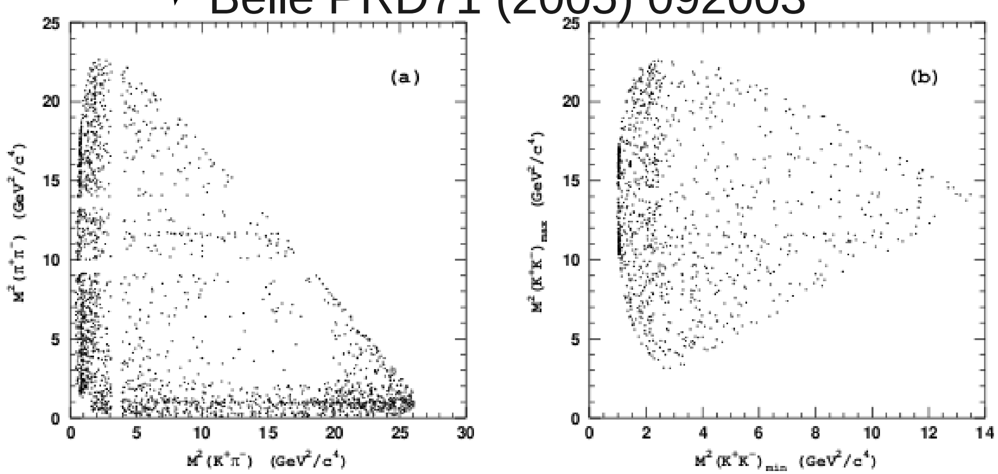
BaBar $B \to \pi^+\pi^-\pi^0$ PRD 76 (2007) 012004



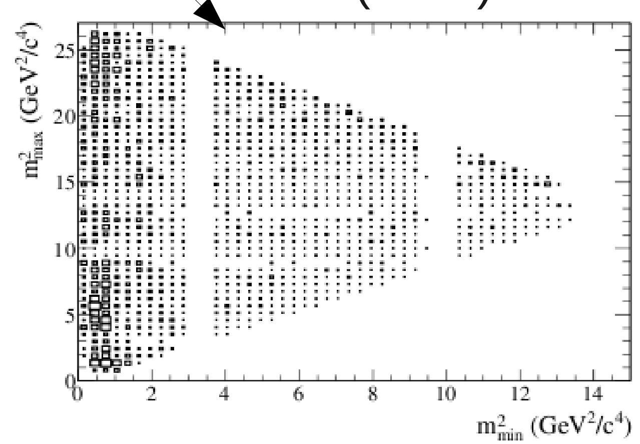
Visualisation of the Dalitz plot

- Obviously important to present the data to the world
- How to present it?
  - 2D scatter plot of events in the signal region
    - unbinned, hence most information
    - but contains background and not corrected for efficiency
  - Binned 2D (or 1D) projections
    - can correct for background and efficiency
      - sPlots is a useful tool
    - but tend to wash out some of the fine structure

Belle PRD71 (2005) 092003



BaBar PRD 79 (2009) 072006

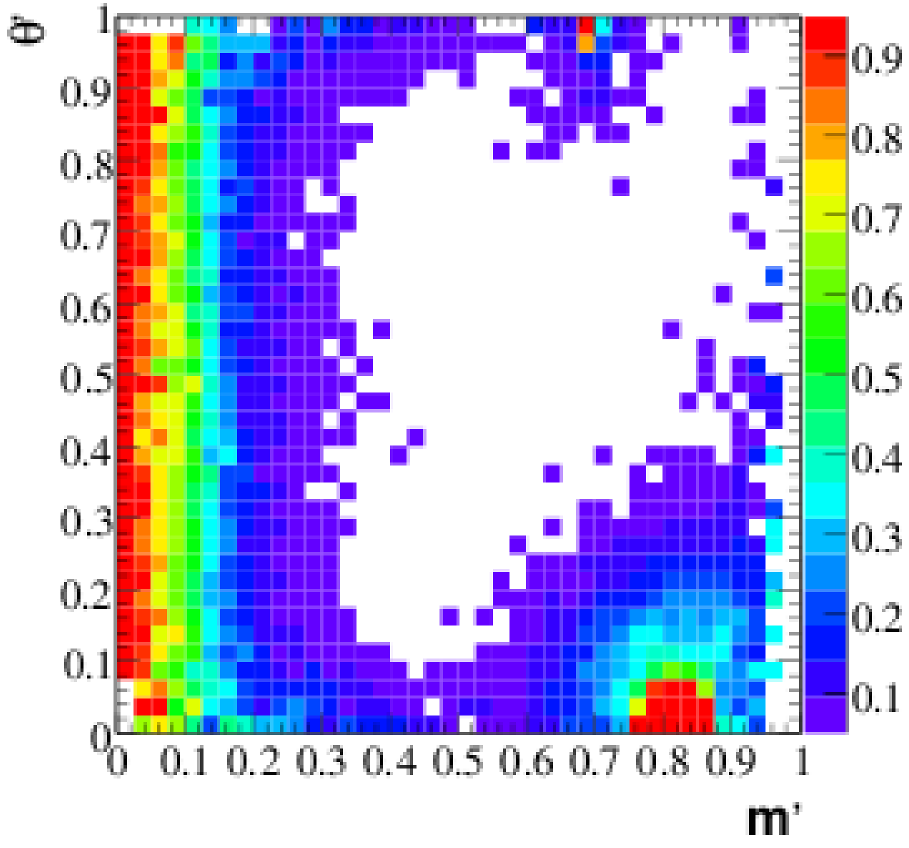


Resolution and misreconstruction

- Key point:
  - If resolution is << width of narrowest structure on the Dalitz plot, we can ignore it
- Applying 3-body mass constraint helps, but
  - Some Dalitz plots contain narrow structures (ω, φ, D*)
  - Misreconstruction effects (“self-cross-feed”) can lead to significant non-Gaussian tails
    - complicated smearing of events across the Dalitz plot
    - hard to model
    - relies on Monte Carlo simulation – hard to validate with data
    - significant for states with multiple soft particles at B factories

Example SCF fraction

BaBar $B \to K^+\pi^-\pi^0$ PRD 78 (2008) 052005



Parametrisations

- Fit parameters are complex coefficients of the contributing amplitudes
  - allowing for CP violation, 4 parameters for each
    - usually necessary to fix (at least) two reference parameters
  - many possible parametrisations
    - $r \exp(i\delta) \rightarrow (r \pm \Delta r) \exp(i(\delta \pm \Delta\delta))$
    - $r \exp(i\delta) \rightarrow r \exp(i\delta)(1 \pm \Delta\rho \exp(i\Delta\varphi))$
    - $x+iy \rightarrow (x \pm \Delta x)+i(y \pm \Delta y)$
  - there is no general best choice of “well-behaved parameters”
    - unbiased, Gaussian distributed, uncertainties independent of other parameters
    - (correlations allowed in Gaussian limit – important to report full covariance matrix)
  - some partial solutions available, but often not applicable
    - e.g. Snyder-Quinn parametrisation for $B \rightarrow \pi^+\pi^-\pi^0$
      - #parameters explodes for >3 resonances

Conventions

- There are many different ways to write the lineshapes, spin factors, etc.
  - choice of normalisation is important
- Even if all code is bug-free, it is very hard to present unambiguously all information necessary to allow the Dalitz plot model to be reproduced
- Important to present results in convention-independent form (as well as other ways)
  - e.g. fit fractions and interference fit fractions

Example fit fraction matrix

TABLE I: Fit fractions matrix of the best fit. The diagonal elements F_{kk} correspond to component fit fractions shown in the paper in Table I. The off-diagonal elements give the fit fractions of the interference terms defined as $F_{kl} = 2\Re \int \mathcal{M}_k \mathcal{M}_l^* ds_{23} ds_{13} / \int |\mathcal{M}|^2 ds_{23} ds_{13}$.

$F_{kl} \times 100\%$	ϕ	$f_0(980)$	$X_0(1550)$	$f_0(1710)$	χ_{c0}	NR
ϕ	**11.8 ± 0.9 ± 0.8**	−0.94 ± 0.18 ± 0.11	−1.71 ± 0.36 ± 0.24	0.01 ± 0.10 ± 0.03	0.11 ± 0.02 ± 0.05	3.54 ± 0.38 ± 0.40
$f_0(980)$		**19 ± 7 ± 4**	53 ± 12 ± 7	−4.5 ± 2.9 ± 1.2	−0.9 ± 0.2 ± 0.5	−85 ± 21 ± 14
$X_0(1550)$			**121 ± 19 ± 6**	−30 ± 11 ± 4	−1.1 ± 0.3 ± 0.5	−140 ± 26 ± 7
$f_0(1710)$				**4.8 ± 2.7 ± 0.8**	−0.10 ± 0.07 ± 0.07	4 ± 6 ± 3
χ_{c0}					**3.1 ± 0.6 ± 0.2**	3.9 ± 0.4 ± 1.9
NR						**141 ± 16 ± 9**

Goodness of fit

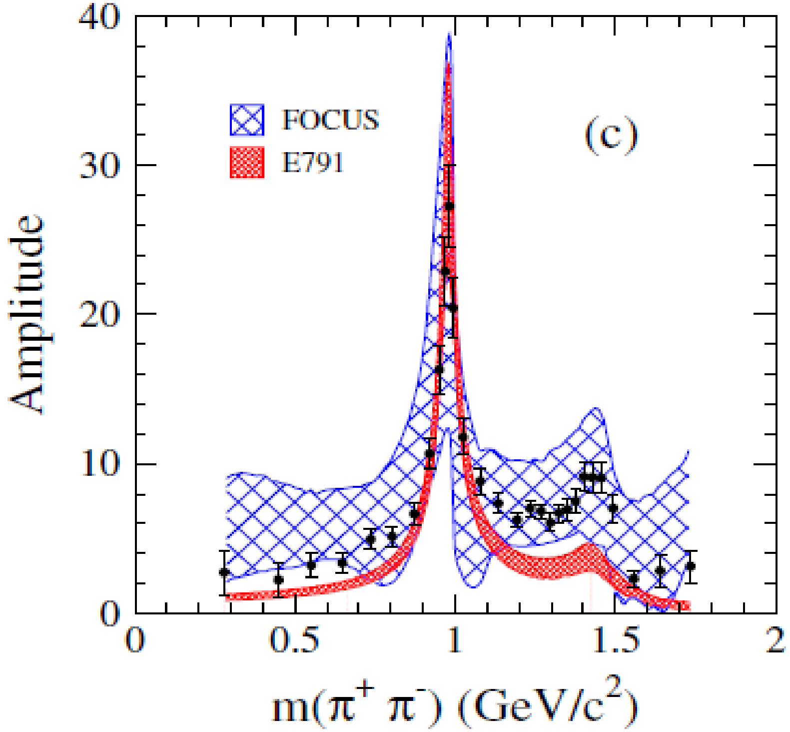
- How do I know that my fit is good enough?
- You don't (sorry) … but some guidelines can tell you if there are serious problems
  - Is your fit model physical?
    - sometimes there may be little choice but to accept this
  - Do you get an acceptable χ^2/n.d.f. for various projections (1D and 2D)?
    - if no, is the disagreement localised in the Dalitz plot?
    - with high statistics it is extremely difficult to get an acceptable p-value; check if the disagreement is compatible with experimental systematics
    - some unbinned goodness-of-fit tests are now becoming available
  - Do you get an excessive sum of fit fractions?
    - values >100% are allowed due to interference, but very large values are usually indicative of unphysical interference patters (possibly because the model is not physical)
  - Do you think you have done the best that you possibly can?
    - eventually it is better to publish with an imperfect model than to suppress the data

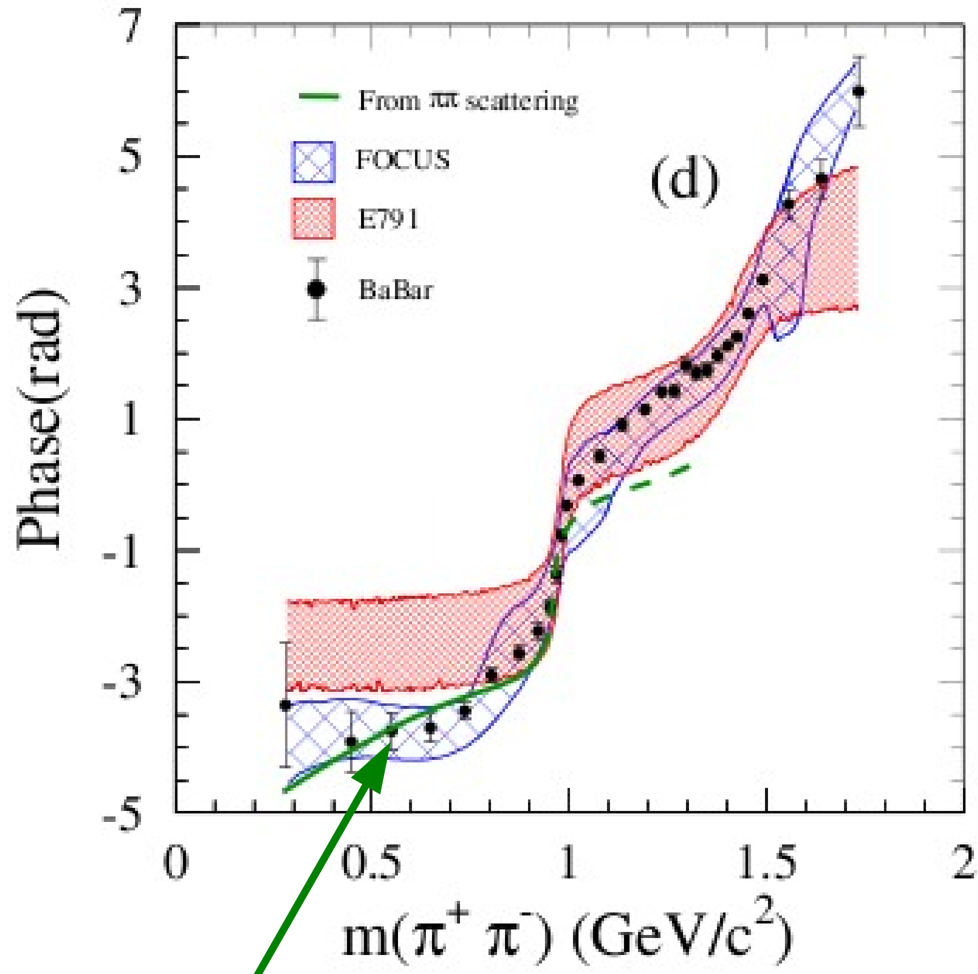
Summary

- It must be clear by now that Dalitz plot analyses are extremely challenging
  - both experimentally and theoretically
- So let's recall that the motivation justifies the effort
  - hadronic effects: improved understanding of QCD, including possible exotic states
  - CP violation effects: potential sensitivity to discover new sources of matter-antimatter asymmetry
- We have an obligation to exploit the existing and coming data to the maximum of our abilities
  - and if that is not enough, we will have to improve our abilities!

THE END

ππ S-wave comparison





Data poin

Prediction from theory:
Kaminski et al. PRD77:054015,2008