Particle properties

- Once a particle has been identified (either directly or through its decay products), it is interesting to measure its properties:
  - Mass $\boldsymbol{M}$
  - Total Decay Width $\boldsymbol{\Gamma}$
  - LifeTime $\boldsymbol{\tau}$
  - Couplings $\boldsymbol{g}$
- If the particle is identified through its decay, all these parameters can be obtained through a dedicated analysis of the kinematics of its decay products.

Invariant Mass - I

- Suppose that a particle *X* decays to a number of particles (***N***), and assume we can measure the quadri-momenta of all them. We can evaluate the Invariant Mass of X for all the candidate events of our final sample:

$$M_{inv}^2 = \left(\sum_{k=1}^{N} \tilde{p}_k \right)^2$$

- It is a relativistically invariant quantity. In case of N = 2

$$M_{inv}^2 = m_1^2 + m_2^2 + 2\left(E_1 E_2 - \vec{p}_1 \cdot \vec{p}_2\right)$$

- If N=2 and the masses are 0 or very small compared to p

$$M_{inv}^2 = 2E_1E_2\left(1-\cos\theta\right) = E_1E_2\sin^2 \theta/2$$

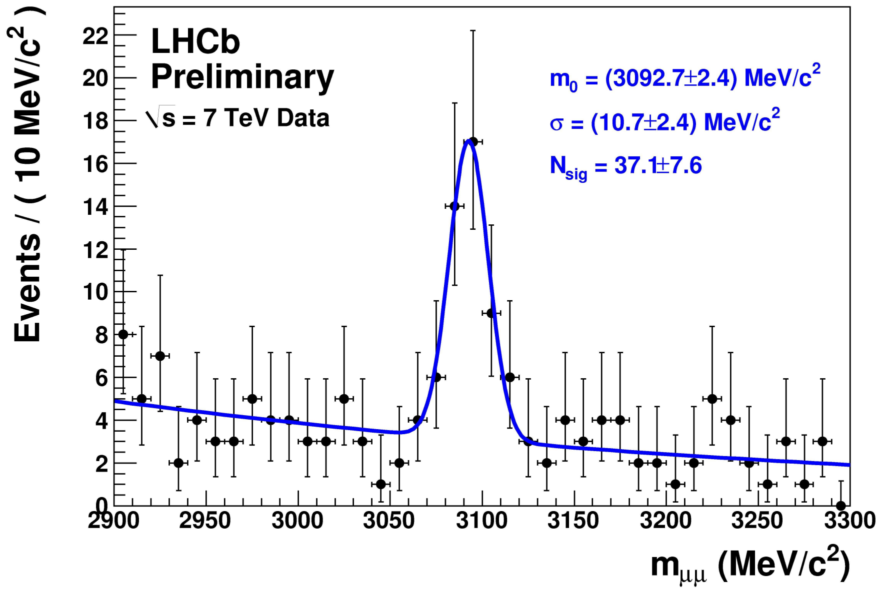
- Where $\boldsymbol{\theta}$ is the opening angle between the two daughter particles.

Invariant Mass - II

- Given the sample of candidates, we do the invariant mass distribution and we typically get a plot like that:

  - A peak (the signature of the particle)
  - A background (almost flat in this case) ➔ **irreducible** background.

$B^{+} \Rightarrow J/\psi \;\; K^{+}$



- What information can we get from this plot (by fitting it) ?

(1) Mass of particle;

(2) Width of the particle (BUT not in this case…);

(3) Number of particles produced (related to $\boldsymbol{\sigma}$ or $\boldsymbol{BR}$)

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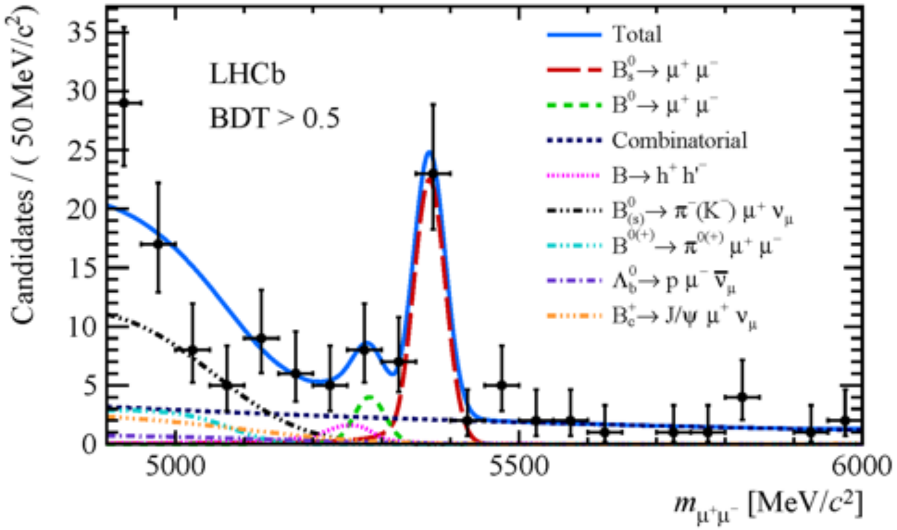

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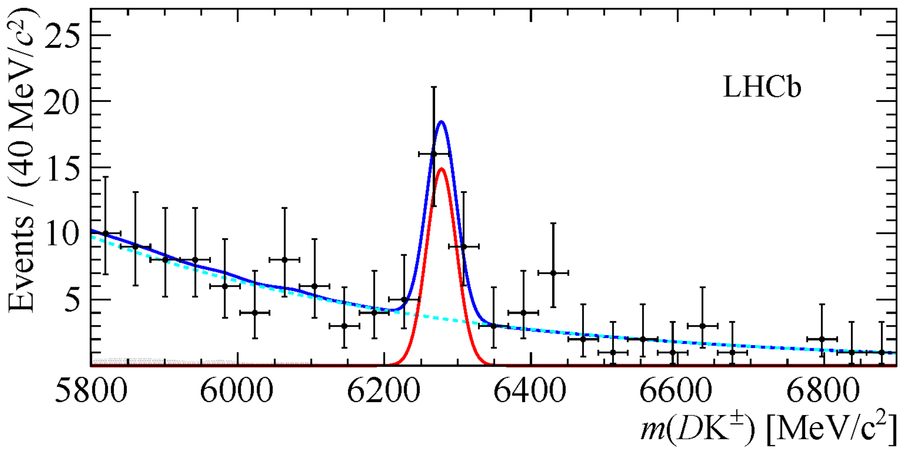

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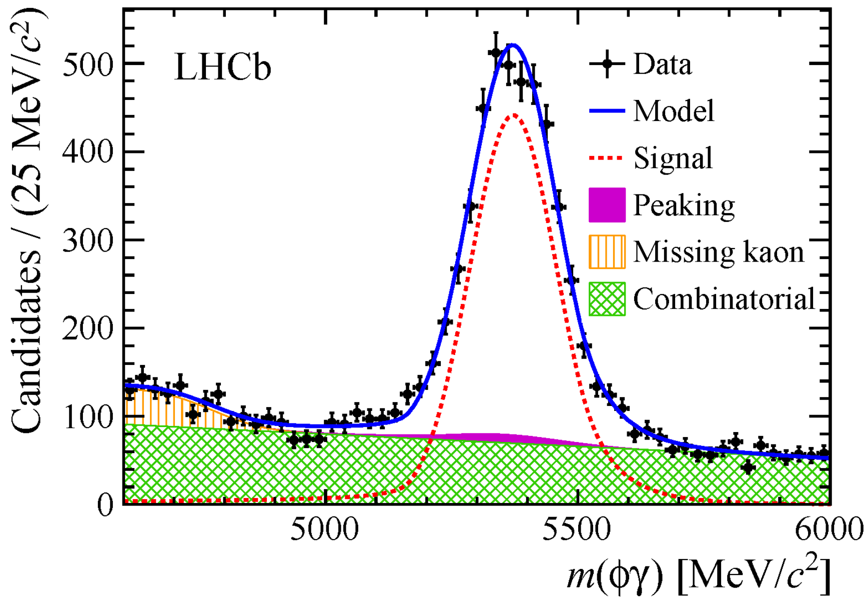

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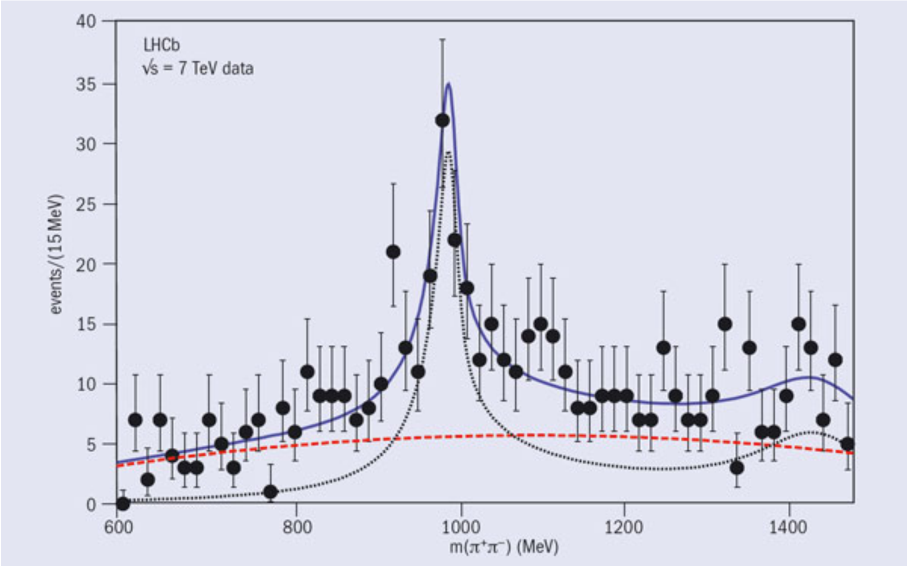
$B^0_s \to J/\psi\ f_0(980)$



(1) Mass of particle;

(2) Width of the particle (BUT not in this case…);

(3) Number of particles produced (related to $\boldsymbol{\sigma}$ or ***BR***)

Suppose Poisson variable and n=0 is measured (no background)
=> 0±0 (freq) or 1±1 (Bayes) ?

Upper limit (lower limit =0)

By construction the probability to measure $x_0' < x_0$ if the true value $\mu = \mu_1(x_0)$ is (1-α) (only one limit) or the probability to measure $x_0' > x_0$ if the true value $\mu = \mu_1(x_0)$ is α

$$P(n > 0/\lambda) = \sum_{n=1}^{\infty} \frac{\lambda^n e^{-\lambda}}{n!} = 1 - e^{-\lambda} = \alpha$$

frequentist

$$\bar{\lambda} = -\ln(1-\alpha)$$

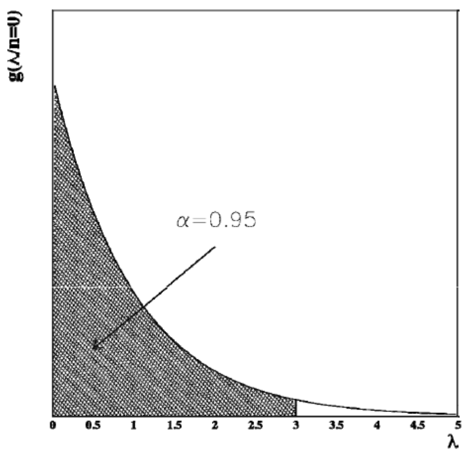
$$g(\lambda / n = 0) = \frac{p(n=0/\lambda) f_0(\lambda)}{\int_0^{\infty} p(n=0/\lambda) f_0(\lambda) d\lambda} = \frac{e^{-\lambda}}{\int_0^{\infty} e^{-\lambda} d\lambda} = e^{-\lambda}$$

Bayesian
(uniform prior)

$$p(\lambda < \bar{\lambda}) = \int_0^{\bar{\lambda}} e^{-\lambda} d\lambda = 1 - e^{-\bar{\lambda}} = \alpha$$

	90%	95%	99%
$\bar{\lambda}$	2.3	3.0	4.6

$\underline{\lambda}$ (68.3%)=1.15



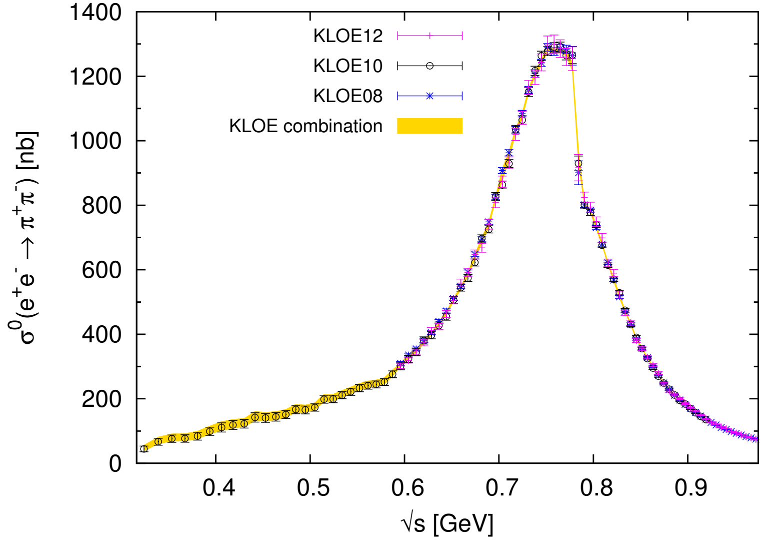
Parenthesys: 2 kinds of background

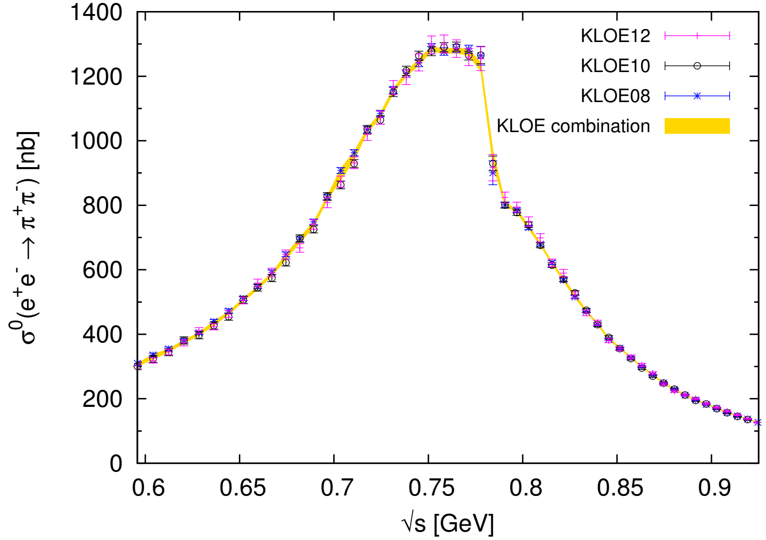
- ***Irreducible background***: same final state as the signal, no way to disentangle. The only way to separate signal from unreducible background is to fit the inv.mass spectrum
- ***Reducible background***: a different final state that mimic the signal (e.g. because you are losing one or more particles, or because you are confusing the nature of one or more particles)
- Example:
  - Signal: pp→H→ZZ*→4l
  - Irreducible background: pp→ ZZ*→4l
  - Reducible backgrounds: pp→Zbb with Z→2l and two leptons, one from each b-quark jet; pp→ tt with each t→Wb→lν"l"j

Irreducible effects ("background"): quantum interference

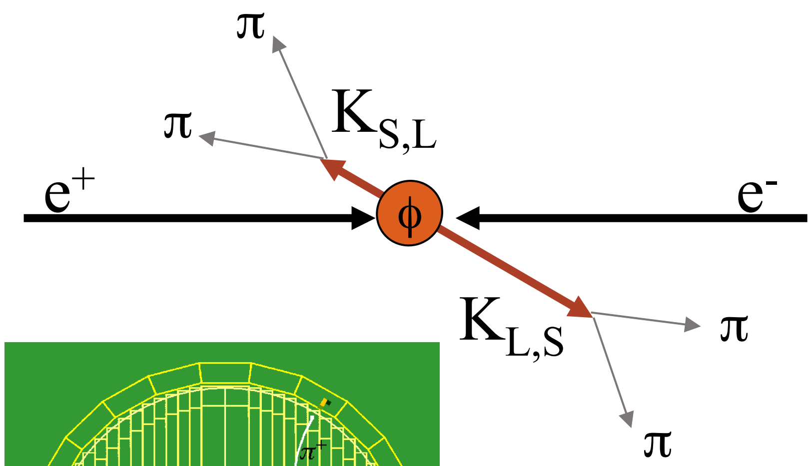
e+e- => π+π− (γ)

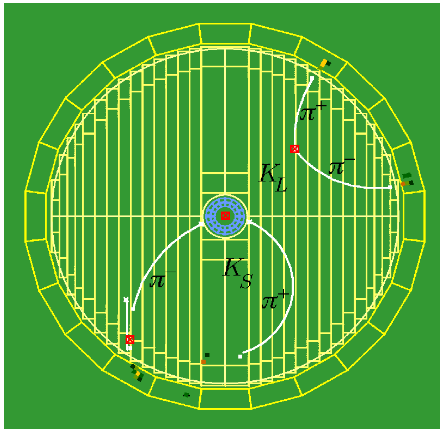
ρ(770) mass 775.26 MeV width 149.1 MeV
ω(782) mass 782.65 MeV width 8.49 MeV

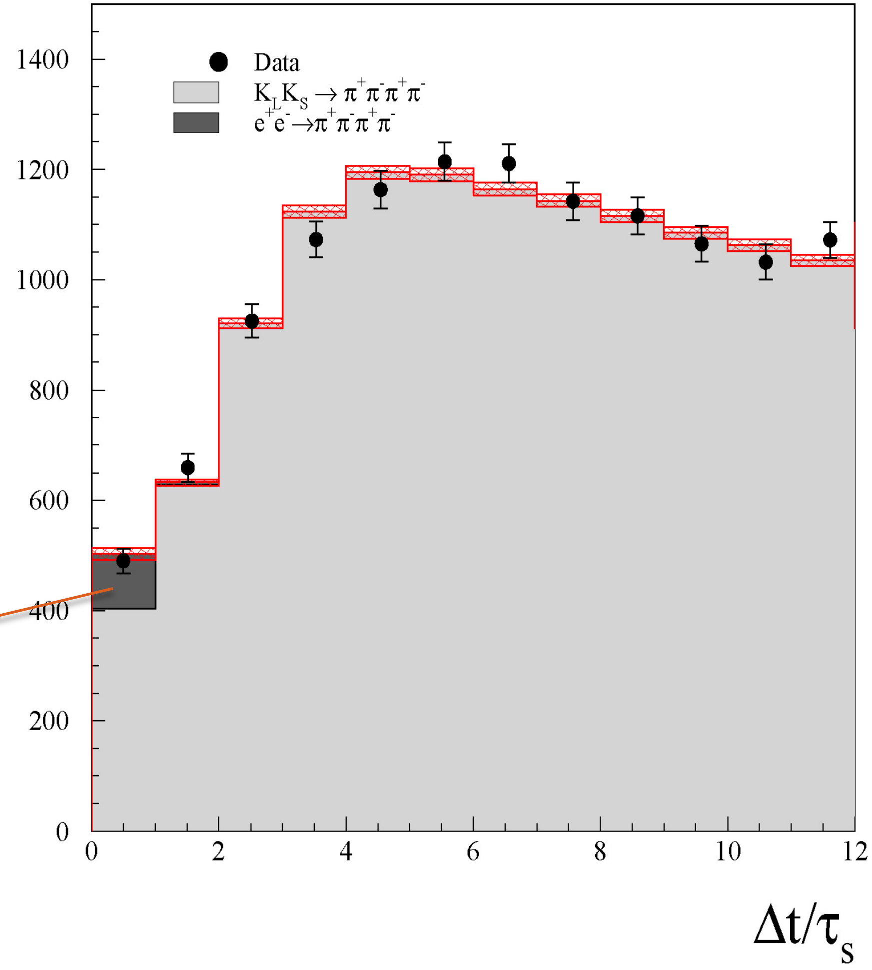




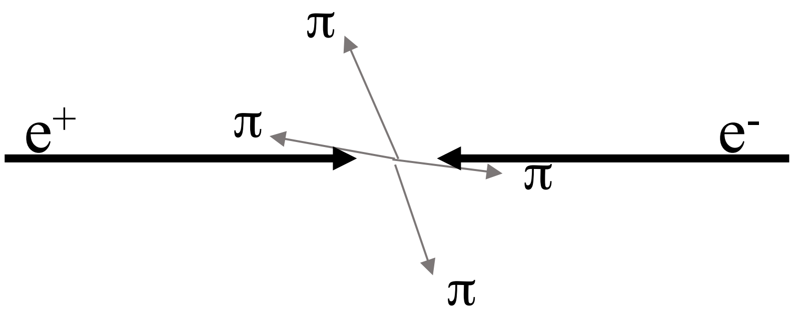
Irreducible or Reducible background?







Background
$e^+e^- \Rightarrow \pi^+\pi^-\pi^+\pi^-$



$$\Delta t = |t_1 - t_2|$$

Mass and Width measurement

- Fit of the M_{inv} spectrum with a Breit-Wigner + a continuos background: BUT careful with mass resolution. It can be neglected only if $\sigma(M_{inv}) << \Gamma$
- If $\sigma(M_{inv}) \approx \Gamma$ or $\sigma(M_{inv}) > \Gamma$ there are two approaches (as we already know):
  - Folding: correct the theoretical distribution to be used in the fit:

$$\sigma_{fit}(E) = \int G_{res}(E - E_0)\,\sigma_{BW}(E_0)\,dE_0$$

  - Unfolding: correct the experimental data and fit with the theoretical function.
  - Use a gaussian (or a "Crystal Ball" function) neglecting completely the width.
- In many cases only the mass is accessible: the uncertainty on the mass is the one given by the fit (taking into account the statistics) + possible scale systematics.

Gaussian vs. Crystal Ball

- Gaussian: 3-parameters, A, μ, σ. Integral $=A\sigma\sqrt{2\pi}$

$$f(m/A,\mu,\sigma) = A\exp(-\frac{(m-\mu)^2}{2\sigma^2})$$

- Crystal-Ball: 5-parameters, $\underline{m}$, σ, α, n, N

$$f_{CB}(m,\bar{m},\sigma,\alpha,n) = N\cdot\begin{cases} e^{\frac{-(m-\bar{m})^2}{2\sigma^2}} & \text{for} \quad \frac{n-\bar{m}}{\sigma} > -\alpha \\ A\cdot(B-\frac{m-\bar{m}}{\sigma})^{-n} & \text{for} \quad \frac{n-\bar{m}}{\sigma} \leq -\alpha \end{cases}$$

$$A = (\frac{n}{|\alpha|})^n e^{-\frac{\alpha^2}{2}},\ B = \frac{n}{|\alpha|} - |\alpha|$$

(Gaussian core + power law tail)

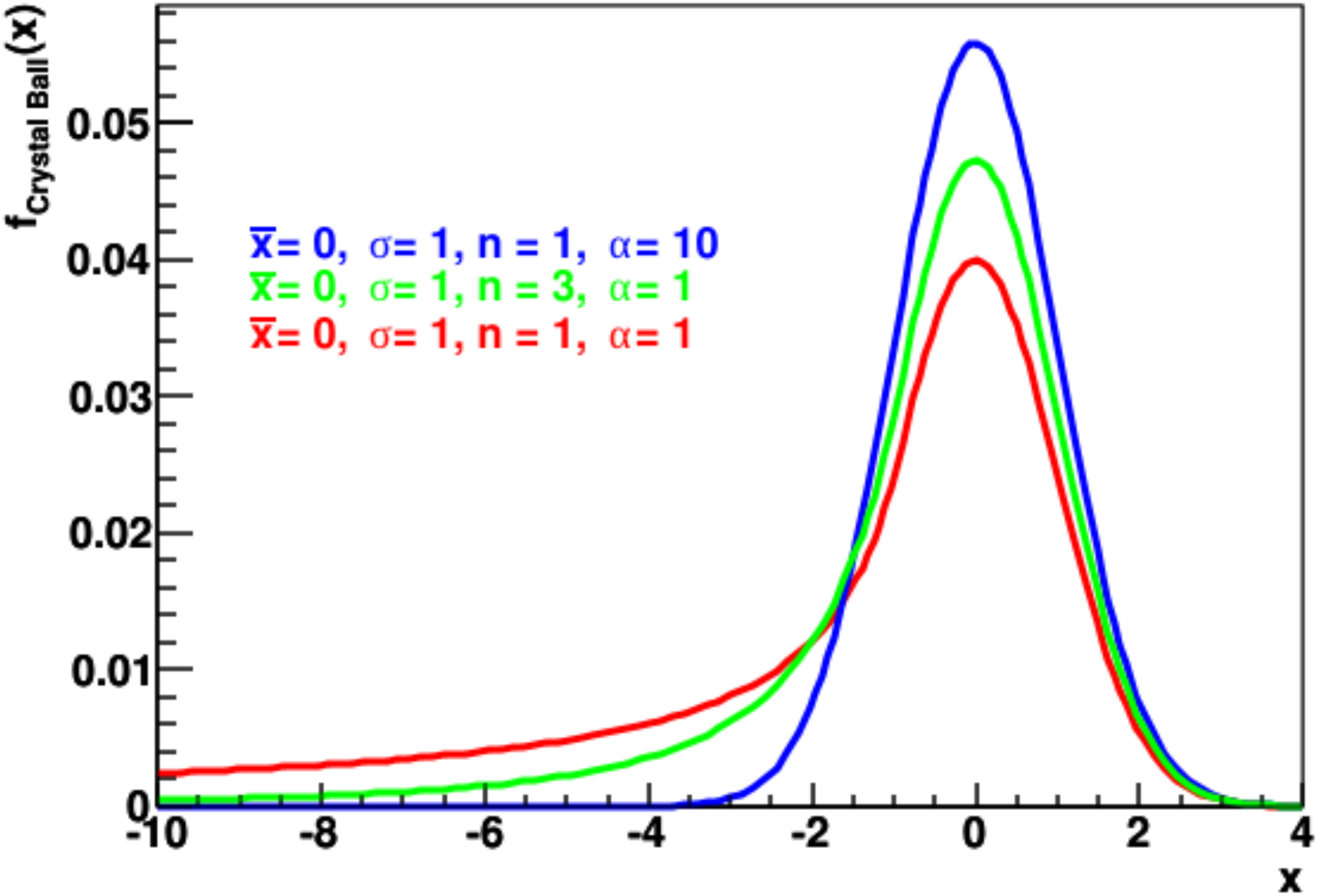
Essentially takes into account energy losses, useful in many cases.

(in this case σ is not the gaussian standard deviation with 68% c.l.)

Crystal-Ball function and its first derivative are both continuos.

After Crystal-Ball collaboration, Crystal Ball hermetic NaI detector at SPEAR Stanford 1979 (then DESY, AGS-BNL, A2-Mainz Microtron…)

Crystal Ball function



Effect of the mass resolution on the significativity of a signal

- Let's consider now the case in which we look for a process and we expect a peak in a distribution at a definite mass: when may we say that we have observed that process ?
- Method of assessment: simple fit S+B (e.g. template fit).
  $S \pm \sigma(S)$ away from 0 at least 3 (5) standard deviations.
- Ingredients:
  - Mass resolution;
  - Background

$$\sigma^2(S) = \sigma^2(N) + \sigma^2(B) = N + \sigma^2(B)$$

neglecting $\sigma(B)$ $\approx N = S + B = S + 6\sigma_M b$

- Effect of mass resolution negligible on the uncertainty on S if:

$$S >> 6b\sigma_M \quad \Rightarrow \quad \sigma_M << \frac{S}{6b}$$

Background b= 50 /MeV in an interval of 60 MeV (+/- 3*10 MeV) B=b*60 MeV = 3000 (broad)
in an interval of 12 MeV (+/- 3*2 MeV) B=b*12 MeV = 600 (narrow)

Signal S=200

Significance = 3.5 (broad) and 7.1 (narrow)

S/6b = 0.67 MeV => in both cases σ_M <<S/6b not satisfied => resolution effect important and observation of the signal can be improved reducing the resolution

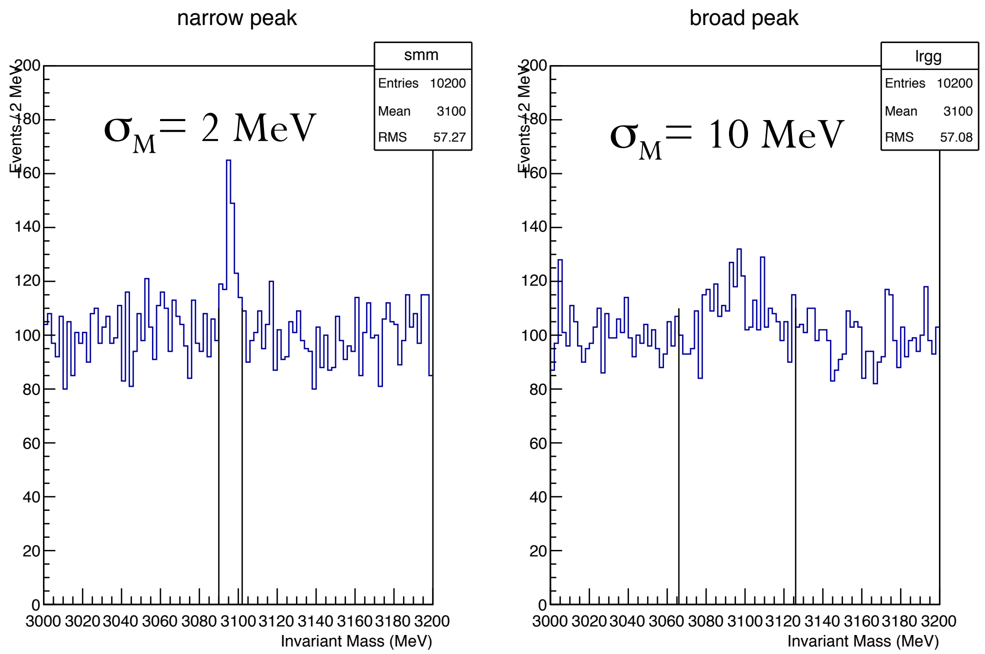


FIGURE 8. Simulation of $S = 200$ J/ψ events superimposed to a flat background of 10000 distributed on a range of 200 MeV (b=50 MeV−1). $\sigma_M = 2$ MeV (left) and $\sigma_M = 10$ MeV (right). The limits of $\pm 3\sigma_M$ intervals around the expected position of the peak are shown. Outside these limits are the sidebands.

$H \rightarrow \gamma\gamma$ ATLAS: is the resolution negligible ?

Numbers directly from the plot:

$S \approx 1000$

$b \approx 5000/2$ GeV

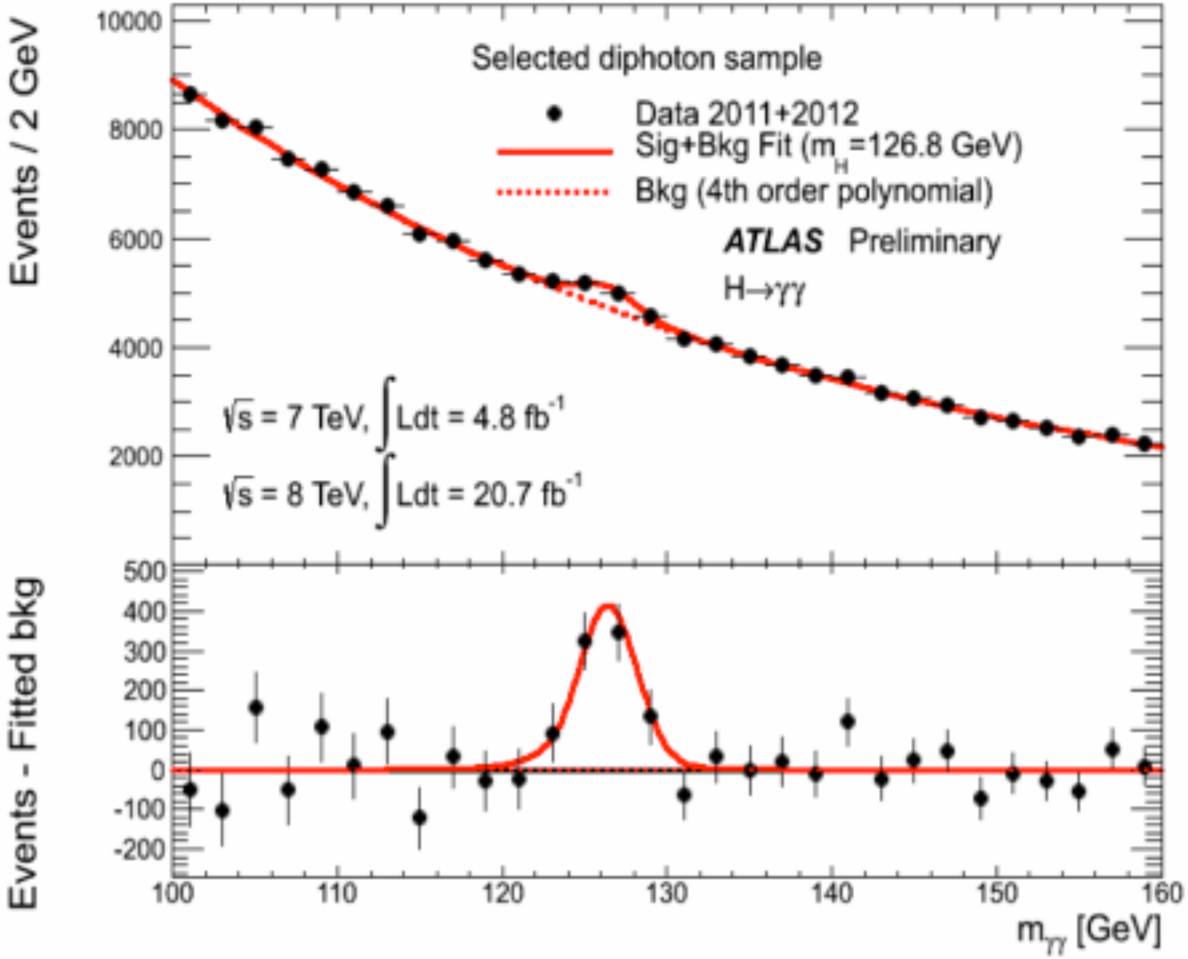
$= 2500/$GeV

$\sigma_M \approx 10$ GeV$/6$

$=1.7$ GeV

➔ $S/6b$

$= 0.07$ GeV $<< \sigma_M$



($B=6\sigma_M b \approx 25000$ => Significance$=6.2$)

Template fits: not functions but histograms

In this case the fit is not done with a function with parameters BUT it is a "template" fit:

$$F = \boldsymbol{a}\text{HIST1}(\boldsymbol{m_H}, \ldots) + \boldsymbol{b}\text{HIST2}$$

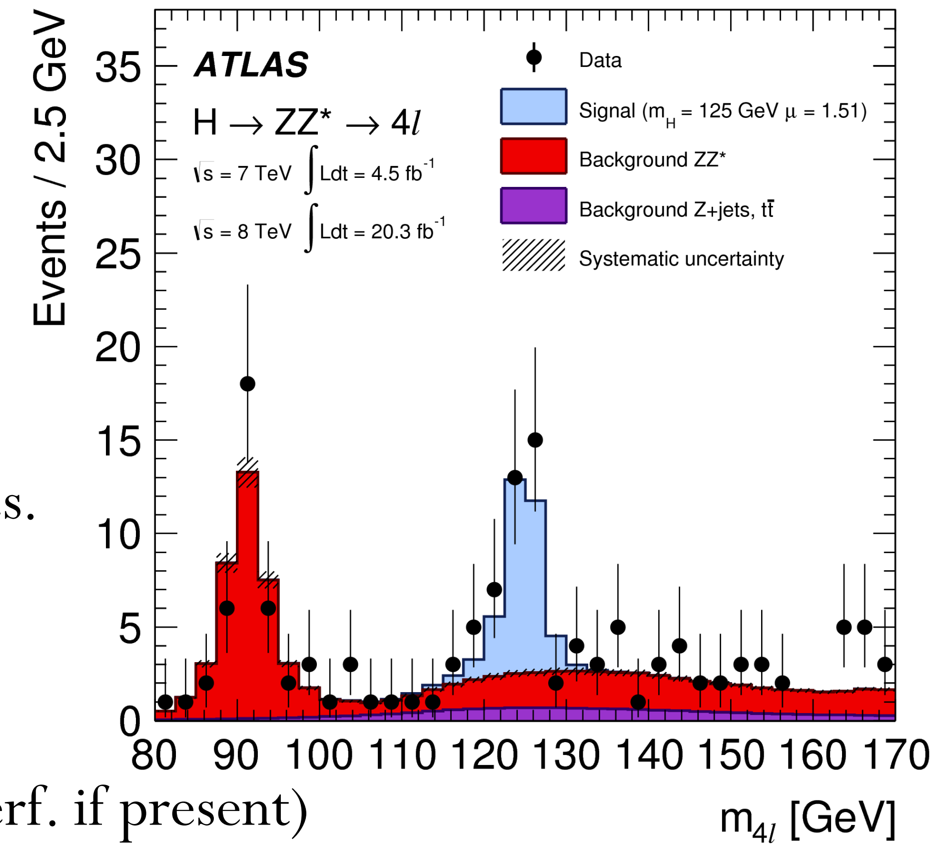
$\boldsymbol{a}$, $\boldsymbol{b}$ and $\boldsymbol{m_H}$ are free parameters.

The method requires the knowledge (from MC) of the expected distributions ("shapes"). Such a knowledge improves our uncertainties.

NB: HIST1 and HIST2 take into account experimental resolution: so it is directly the folding method.

(NB2: take into account also QM interf. if present)

An example: Higgs mass in the 4l channel.

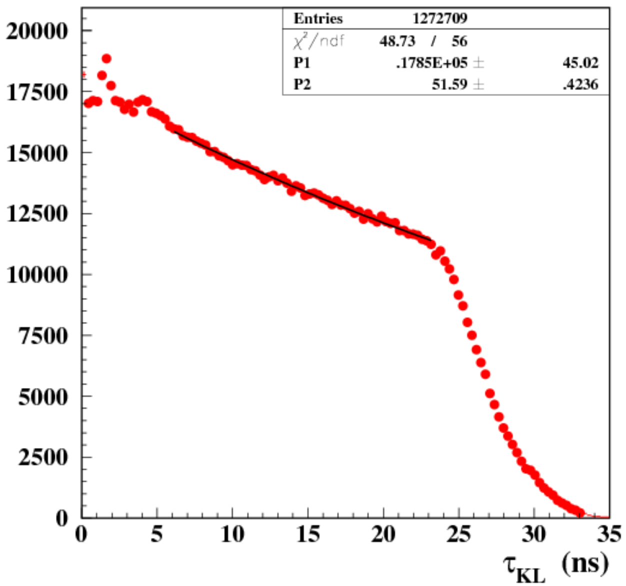


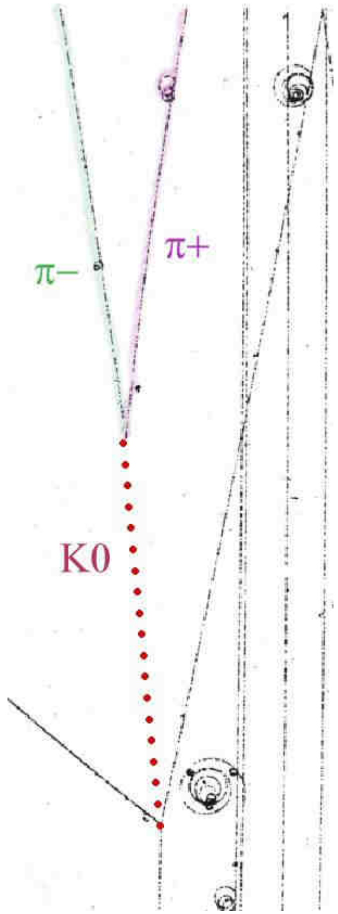
Lifetime measurement - I

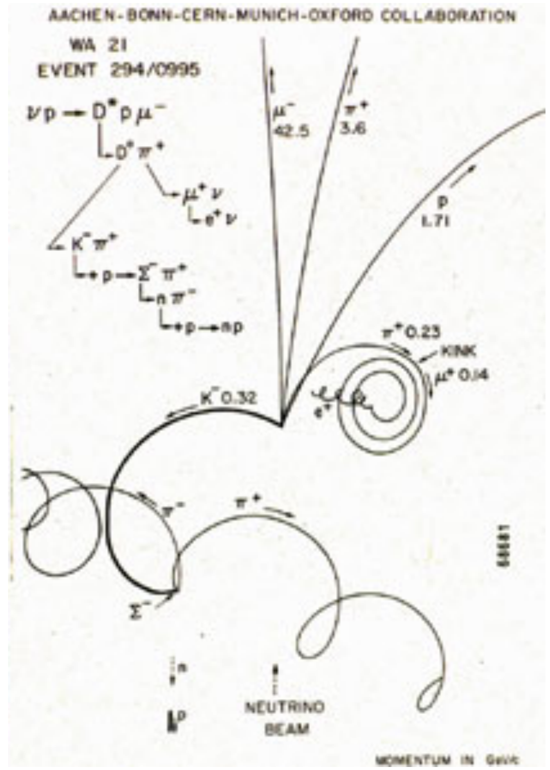
→ In the first decades of EPP, bubble-chambers and emulsions allowed to see directly the decay length of a particle either neutral or charged (see Kaons);

→ The decay length *l* is related to the lifetime through the $L = \beta\gamma\tau c$ ➔ $\tau = L / \beta\gamma c$

→ For a sample of particles produced we expect an exponential distribution







Lifetime measurement - II

- Example: pions, kaons, c and b-hadrons in the LHC context (momentum range 10 ÷ 100 GeV).

	π^+	K^+	D^+	B^+
Mass (GeV)	0.140	0.494	1.869	5.279
Life Time (s)	2.6×10^{-8}	1.2×10^{-8}	1.0×10^{-12}	1.6×10^{-12}
Decay length (m) p = 10 GeV	557	72.8	1.6×10^{-3}	9.1×10^{-4}
Decay length (m) p = 100 GeV	5570	728	0.016	0.0091

NB When going to c or b quarks, decay lengths O(<mm) are obtained
➔ Necessity of dedicated "vertex detectors"

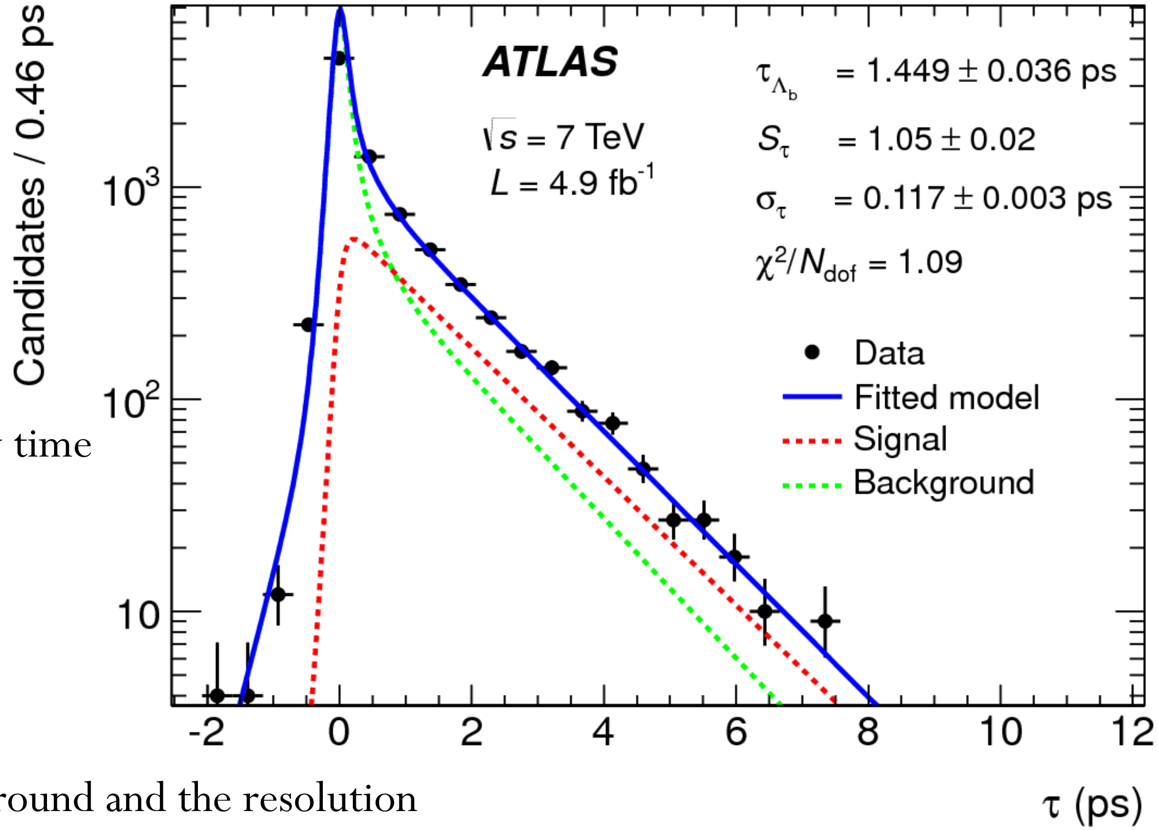
Lifetime measurement - III

For low-τ particles
(e.g. B-hadrons, τ, …):
→ define the proper decay time
($\beta\gamma$=p/m):

$$\tau = \frac{Lm}{p}$$

At hadron colliders the proper decay time is defined on the transverse plane:

$$\tau = \frac{L_{xy}m}{p_T}$$

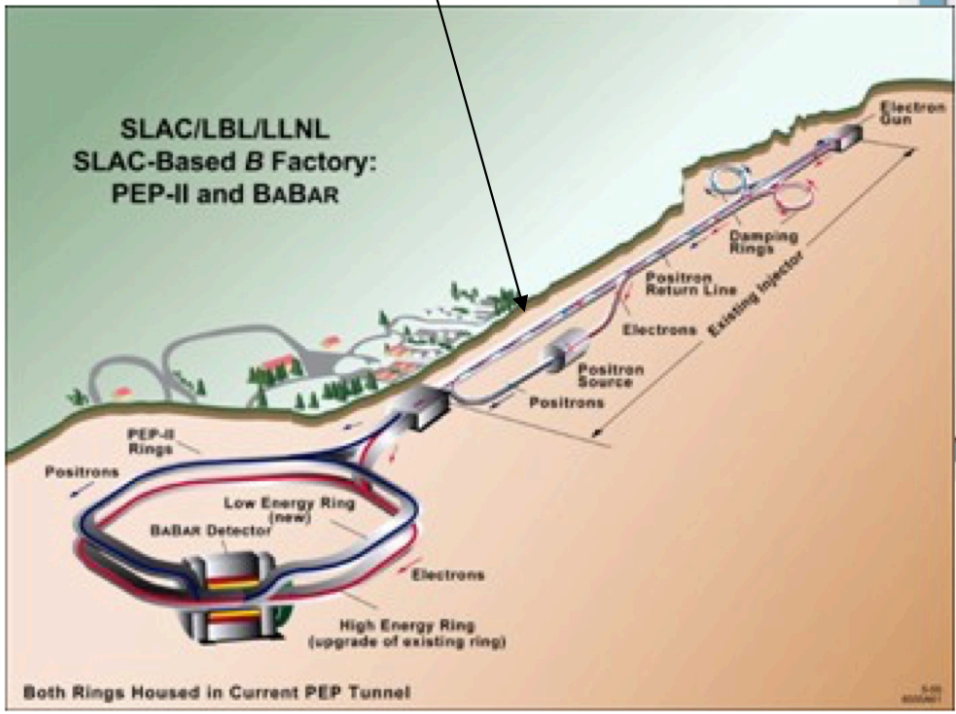


The fit takes into account the background and the resolution

Typical resolutions: O(10^{-13} s) → tens of μm

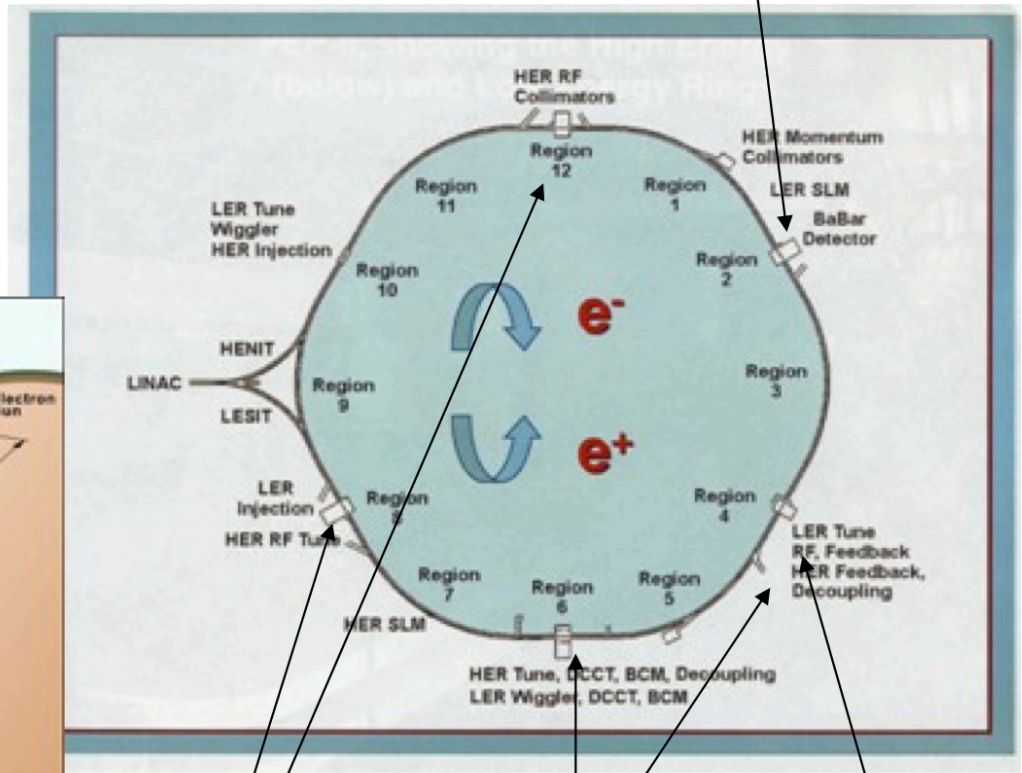
PEP-II e^+e^- Collider

- Use the SLAC linac as upgraded for the SLC for the injector.



C = 2200 m

BaBar Detector



HER RF 476 MHz

Feedbacks Diagnostics

LER RF 476 MHz

3.1 GeV positrons x 9 GeV electrons

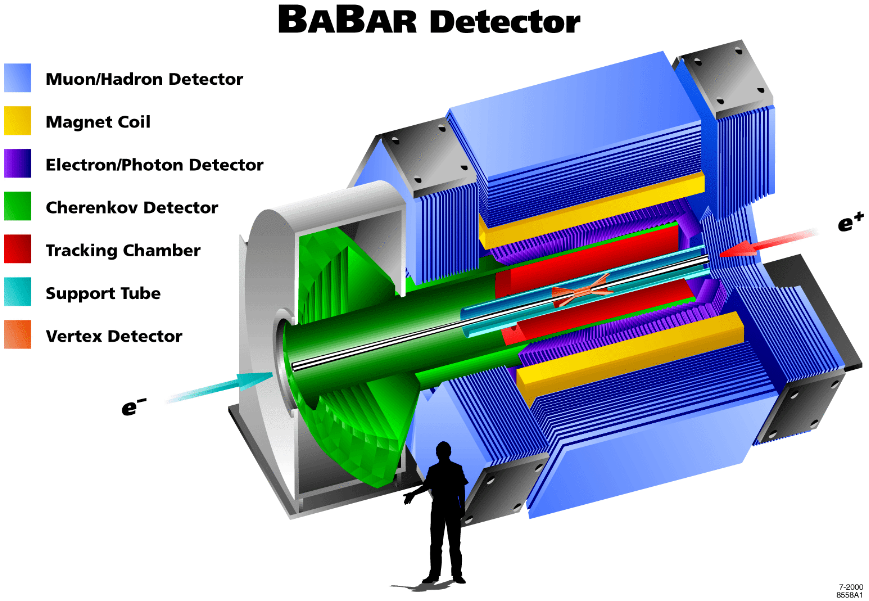
B-factories

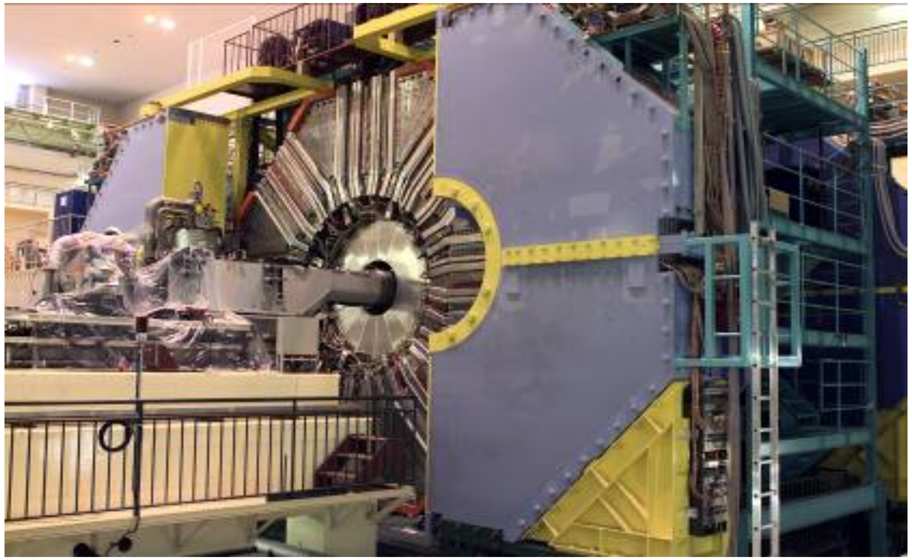
BABAR @ PEP-II

collected L=557 fb^{-1}

BELLE @ KEKB

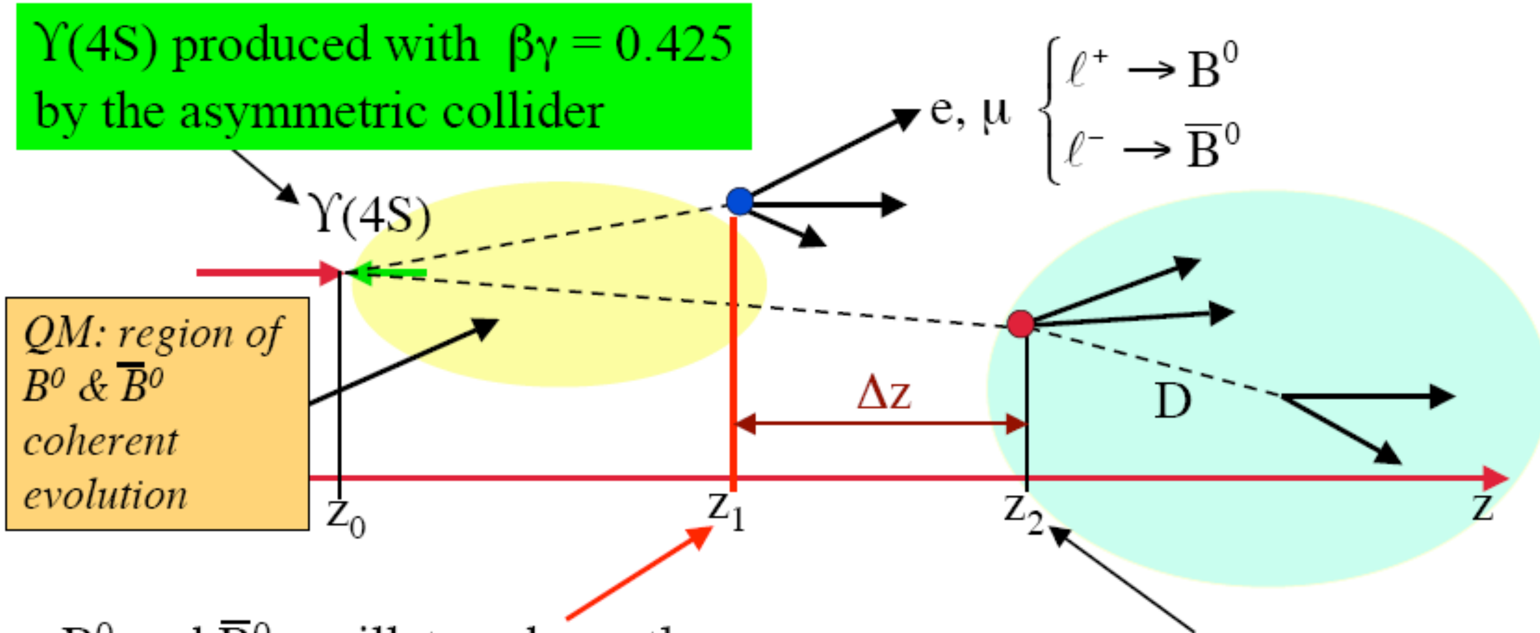
collected L=1040 fb^{-1}





Correlated B meson pairs

B



B^0 and $\bar{B}^0$ oscillate coherently. When the first decays, the other is known to be of the opposite flavour, at the same proper time

Than the other B^0 oscillates freely before decaying after a time given by

$\Delta t = \Delta z / \langle \beta\gamma \rangle c$ $\quad \langle \beta\gamma \rangle = 0.55$ for B mesons

N.B. : production vertex position z_0 not very well known : only Δz is available !

Efficiency measurement - I

- Suppose you want to measure the detection efficiency of a final state X: X contains N particles e.g. $Z \rightarrow \mu\mu$ contains 2 particles and whatever else. How much is the probability to select an event containing a $Z \rightarrow \mu\mu$?
- Let's suppose that:
  - Trigger is: at least 1 muon with $p_T > 10$ GeV and $|\eta| < 2.5$
  - Offline selection is: 2 and only 2 muons with opposite charge and $M_Z - 2\Gamma < M_{inv} < M_Z + 2\Gamma$
- Approach for efficiency
  - Full event method: apply trigger and selection to simulated events and calculate N_{sel}/N_{gen} (validation is required)
  - Single particle method: (see next slides)

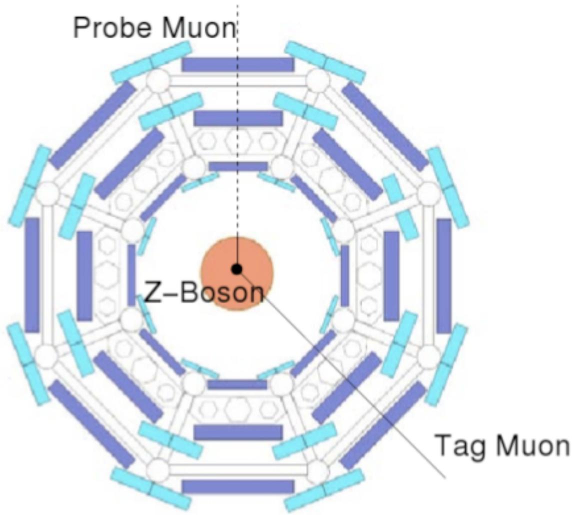
Efficiency measurement - II

- Measure single muon efficiencies as a function of kinematics (p_T, η, …); perform the same "measurement" using simulated data.
  - Tag & Probe method: muon detection efficiency measured using an independent detector and using "correlated" events.
  - Trigger efficiency using "pre-scaled" samples collected with a trigger having a lower threshold.

$$\varepsilon_{trigger} = \frac{\#\mu - triggered}{\#\mu - total}$$

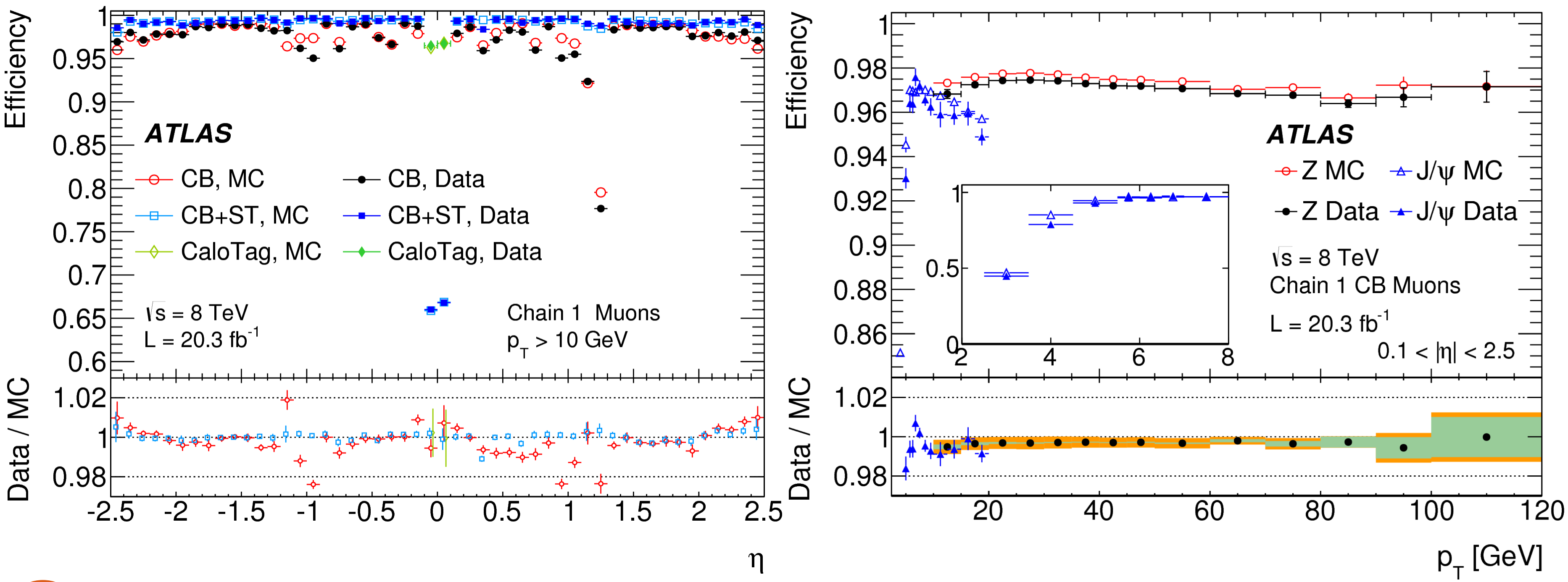
T&P: a "Tag Muon" in the MS and a "Probe" in the ID
Tag+Probe Inv.Mass consistent With a Z boson
➔ There should be a track in the MS

$$\varepsilon_{TP} = \frac{\#\mu - reco}{\#\mu - \text{expected}}$$



Efficiency measurement - III

- Muon Efficiency – ATLAS experiment.
- As a function of η and p_T – comparison with simulation ➔ Scale Factors



Efficiency measurement - IV

- After that I have: $\varepsilon_T(p_T, \eta, \ldots)$ and $\varepsilon_S(p_T, \eta, \ldots)$
- From MC I get the expected kinematic distributions of the final state muons and I apply for each muon its efficiency depending on its p_T and η. The number of surviving events gives the efficiency for X
- Or I simply apply the scale factors to the MC fully simulated events to take into account data-MC differences.

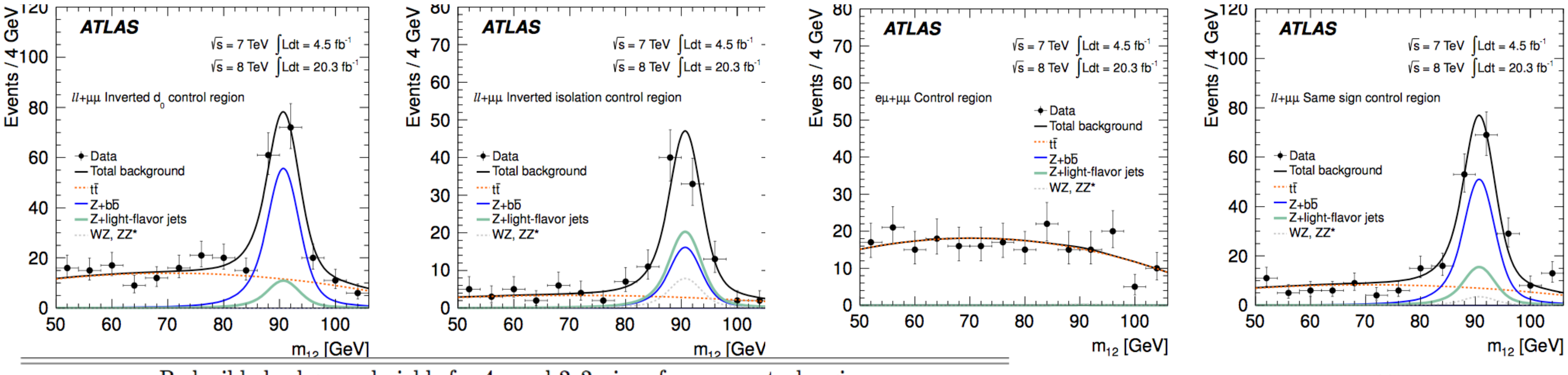
Background measurement - I

- Based on simulations:
  - define all possible background processes (with known cross-sections);
  - apply trigger and selection to each simulated sample;
  - determine the amount of background in the "signal region" after weighting with known cross-sections.
- Data-driven methods:
  - "control regions" based on a different selection (e.g. sidebands);
  - fit control region distributions with simulated distributions and get weigths;
  - then export to "signal region" using "transfer-factors".
- Example: reducible background of H4l ATLAS analysis (next slides)

Background measurement - II

Table 3: Expected contribution of the $\ell\ell + \mu\mu$ background sources in each of the control regions.

Background	Control region: Inverted d_0	Inverted isolation	$e\mu + \mu\mu$	Same-sign
$Zb\bar{b}$	$32.8 \pm 0.5\%$	$26.5 \pm 1.2\%$	$0.3 \pm 1.2\%$	$30.6 \pm 0.7\%$
Z + light-flavor jets	$9.2 \pm 1.3\%$	$39.3 \pm 2.6\%$	$0.0 \pm 0.8\%$	$16.9 \pm 1.6\%$
$t\bar{t}$	$58.0 \pm 0.9\%$	$34.2 \pm 1.6\%$	$99.7 \pm 1.0\%$	$52.5 \pm 1.1\%$



Reducible background yields for 4μ and $2e2\mu$ in reference control region

Control region	$Zb\bar{b}$	Z + light-flavor jets	Total Z + jets	$t\bar{t}$
Combined fit	159 ± 20	49 ± 10	208 ± 22	210 ± 12
Inverted impact parameter			206 ± 18	208 ± 23
Inverted isolation			210 ± 21	201 ± 24
$e\mu + \mu\mu$			–	201 ± 12
Same-sign dilepton			198 ± 20	196 ± 22

Extrapolate to "signal region" using transfer factors
➔ (see next slide)

A. $\ell\ell + \mu\mu$ background

The $\ell\ell + \mu\mu$ reducible background arises from $Z +$ jets and $t\bar{t}$ processes, where the $Z +$ jets contribution has a $Zb\bar{b}$ heavy-flavor quark component in which the heavy-flavor quarks decay semileptonically, and a component arising from $Z +$ light-flavor jets with subsequent π/K in-flight decays. The number of background events from $Z +$ jets and $t\bar{t}$ production is estimated from an unbinned maximum likelihood fit, performed simultaneously to four orthogonal control regions, each of them providing information on one or more of the background components. The fit results are expressed in terms of yields in a reference control region, defined by applying the analysis event selection except for the isolation and impact parameter requirements to the subleading dilepton pair. The reference control region is also used for the validation of the estimates. Finally, the background estimates in the reference control region are extrapolated to the signal region.

The control regions used in the maximum likelihood fit are designed to minimize contamination from the Higgs boson signal and the ZZ^* background. The four control regions are

(a) *Inverted requirement on impact parameter significance.* Candidates are selected following the analysis event selection, but (1) without applying the isolation requirement to the muons of the subleading dilepton and (2) requiring that at least one of the two muons fails the impact parameter significance requirement. As a result, this control region is enriched in $Zb\bar{b}$ and $t\bar{t}$ events.

(b) *Inverted requirement on isolation.* Candidates are selected following the analysis event selection, but requiring that at least one of the muons of the subleading dilepton fails the isolation requirement. As a result, this control region is enriched in $Z +$ light-flavor-jet events (π/K in-flight decays) and $t\bar{t}$ events.

(c) *$e\mu$ leading dilepton ($e\mu + \mu\mu$).* Candidates are selected following the analysis event selection, but requiring the leading dilepton to be an electron-muon pair. Moreover, the isolation and impact parameter requirements are not applied to the muons of the subleading dilepton, which are also allowed to have the same or opposite charge sign. Events containing a Z-boson candidate decaying into e^+e^- or $\mu^+\mu^-$ pairs are removed with a requirement on the mass. This control region is dominated by $t\bar{t}$ events.

(d) *Same-sign subleading dilepton.* The analysis event selection is applied, but for the subleading dilepton neither isolation nor impact parameter significance requirements are applied and the leptons are required to have the same charge sign (SS). This same-sign control region is not dominated by a specific background; all the reducible backgrounds have a significant contribution.

PHYSICAL REVIEW D **91,** 012006 (2015)

Measurements of Higgs boson production and couplings in the four-lepton channel in *pp* collisions at center-of-mass energies of 7 and 8 TeV with the ATLAS detector

A. Inclusive analysis

Four-lepton events were selected with single-lepton and dilepton triggers. The p_T (E_T) thresholds for single-muon (single-electron) triggers increased from 18 to 24 GeV (20 to 24 GeV) between the 7 and 8 TeV data, in order to cope with the increasing instantaneous luminosity. The dilepton trigger thresholds for 7 TeV data are set at 10 GeV p_T for muons, 12 GeV E_T for electrons and (6, 10) GeV for (muon, electron) mixed-flavor pairs. For the 8 TeV data, the thresholds were raised to 13 GeV for the dimuon trigger, to 12 GeV for the dielectron trigger and (8, 12) GeV for the (muon, electron) trigger; furthermore, a dimuon trigger with different thresholds on the muon p_T, 8 and 18 GeV, was added. The trigger efficiency for events passing the final selection is above 97% in the 4μ, $2\mu 2e$ and $2e2\mu$ channels and close to 100% in the $4e$ channel for both 7 and 8 TeV data.

Higgs boson candidates are formed by selecting two same-flavor, opposite-sign lepton pairs (a lepton quadruplet) in an event. Each lepton is required to have a longitudinal impact parameter less than 10 mm with respect to the primary vertex, and muons are required to have a transverse impact parameter of less than 1 mm to reject cosmic-ray muons. These selections are not applied to standalone muons that have no ID track. Each electron (muon) must satisfy $E_T > 7$ GeV ($p_T > 6$ GeV) and be measured in the pseudorapidity range $|\eta| < 2.47$ ($|\eta| < 2.7$). The highest-p_T lepton in the quadruplet must satisfy $p_T > 20$ GeV, and the second (third) lepton in p_T order must satisfy $p_T > 15$ GeV ($p_T > 10$ GeV). Each event is required to have the triggering lepton(s) matched to one or two of the selected leptons.

Multiple quadruplets within a single event are possible: for four muons or four electrons there are two ways to pair the masses, and for five or more leptons there are multiple ways to choose the leptons. Quadruplet selection is done separately in each subchannel: 4μ, $2e2\mu$, $2\mu 2e$, $4e$, keeping only a single quadruplet per channel. For each channel, the lepton pair with the mass closest to the Z boson mass is referred to as the leading dilepton and its invariant mass, m_{12}, is required to be between 50 and 106 GeV. The second, subleading, pair of each channel is chosen from the remaining leptons as the pair closest in mass to the Z boson and in the range $m_{\rm min} < m_{34} < 115$ GeV, where $m_{\rm min}$ is 12 GeV for $m_{4\ell} < 140$ GeV, rises linearly to 50 GeV at $m_{4\ell} = 190$ GeV and then remains at 50 GeV for $m_{4\ell} > 190$ GeV. Finally, if more than one channel has a quadruplet passing the selection, the channel with the highest expected signal rate is kept, i.e. in the order 4μ, $2e2\mu$, $2\mu 2e$, $4e$. The rate of two quadruplets in one event is below the per mille level.

Background measurement - III

Table 5: Estimates for the $\ell\ell + \mu\mu$ background in the signal region for the full $m_{4\ell}$ mass range for the $\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV data. The $Z+$jets and $t\bar{t}$ background estimates are data-driven and the WZ contribution is from simulation. The decomposition of the $Z+$jets background in terms of the $Zb\bar{b}$ and the $Z+$ light-flavor-jets contributions is also provided.

Background	4μ	$2e2\mu$
	$\sqrt{s} = 7$ TeV	
$Z+$jets	$0.42 \pm 0.21(\text{stat}) \pm 0.08(\text{syst})$	$0.29 \pm 0.14(\text{stat}) \pm 0.05(\text{syst})$
$t\bar{t}$	$0.081 \pm 0.016(\text{stat}) \pm 0.021(\text{syst})$	$0.056 \pm 0.011(\text{stat}) \pm 0.015(\text{syst})$
WZ expectation	0.08 ± 0.05	0.19 ± 0.10
	$Z+$jets decomposition	
$Zb\bar{b}$	$0.36 \pm 0.19(\text{stat}) \pm 0.07(\text{syst})$	$0.25 \pm 0.13(\text{stat}) \pm 0.05(\text{syst})$
$Z+$ light-flavor jets	$0.06 \pm 0.08(\text{stat}) \pm 0.04(\text{syst})$	$0.04 \pm 0.06(\text{stat}) \pm 0.02(\text{syst})$
	$\sqrt{s} = 8$ TeV	
$Z+$jets	$3.11 \pm 0.46(\text{stat}) \pm 0.43(\text{syst})$	$2.58 \pm 0.39(\text{stat}) \pm 0.43(\text{syst})$
$t\bar{t}$	$0.51 \pm 0.03(\text{stat}) \pm 0.09(\text{syst})$	$0.48 \pm 0.03(\text{stat}) \pm 0.08(\text{syst})$
WZ expectation	0.42 ± 0.07	0.44 ± 0.06
	$Z+$jets decomposition	
$Zb\bar{b}$	$2.30 \pm 0.26(\text{stat}) \pm 0.14(\text{syst})$	$2.01 \pm 0.23(\text{stat}) \pm 0.13(\text{syst})$
$Z+$ light-flavor jets	$0.81 \pm 0.38(\text{stat}) \pm 0.41(\text{syst})$	$0.57 \pm 0.31(\text{stat}) \pm 0.41(\text{syst})$

The "ABCD" factorization method

- Use two variables (var1 and var2) with these features:
  - For the background they are completely independent
  - The signal is localized in a region of the two variables
- Divide the plane in 4 boxes: the signal is on D only

For the background, due to the independence we have few relations:

$$B/D = A/C$$

$$B/A = D/C$$

So: If I count the background (in data) events in regions A,B and C I can extrapolate in the signal region D:

$$D = CB/A$$