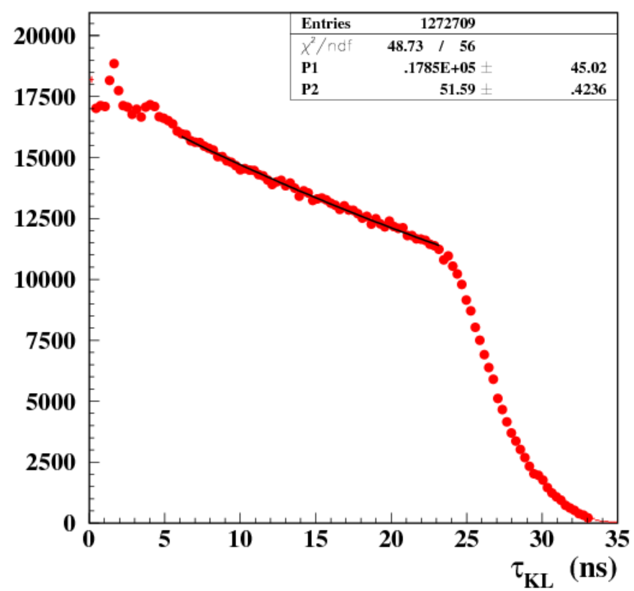
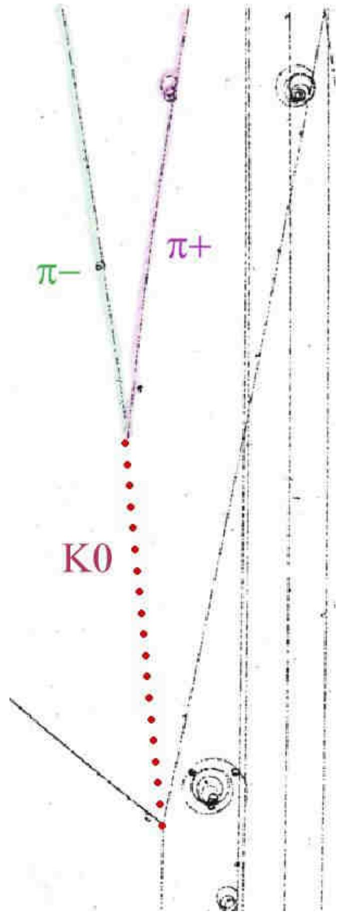
Lifetime measurement - I

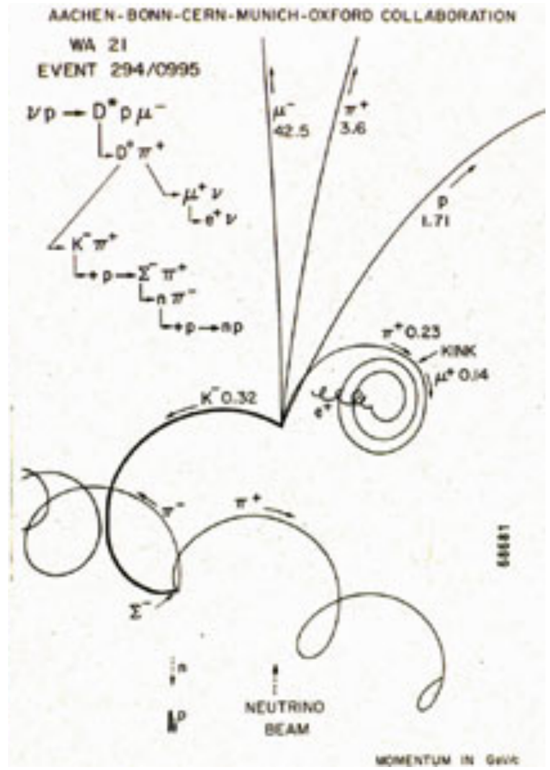
→ In the first decades of EPP, bubble-chambers and emulsions allowed to see directly the decay length of a particle either neutral or charged (see Kaons);

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

→ 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"

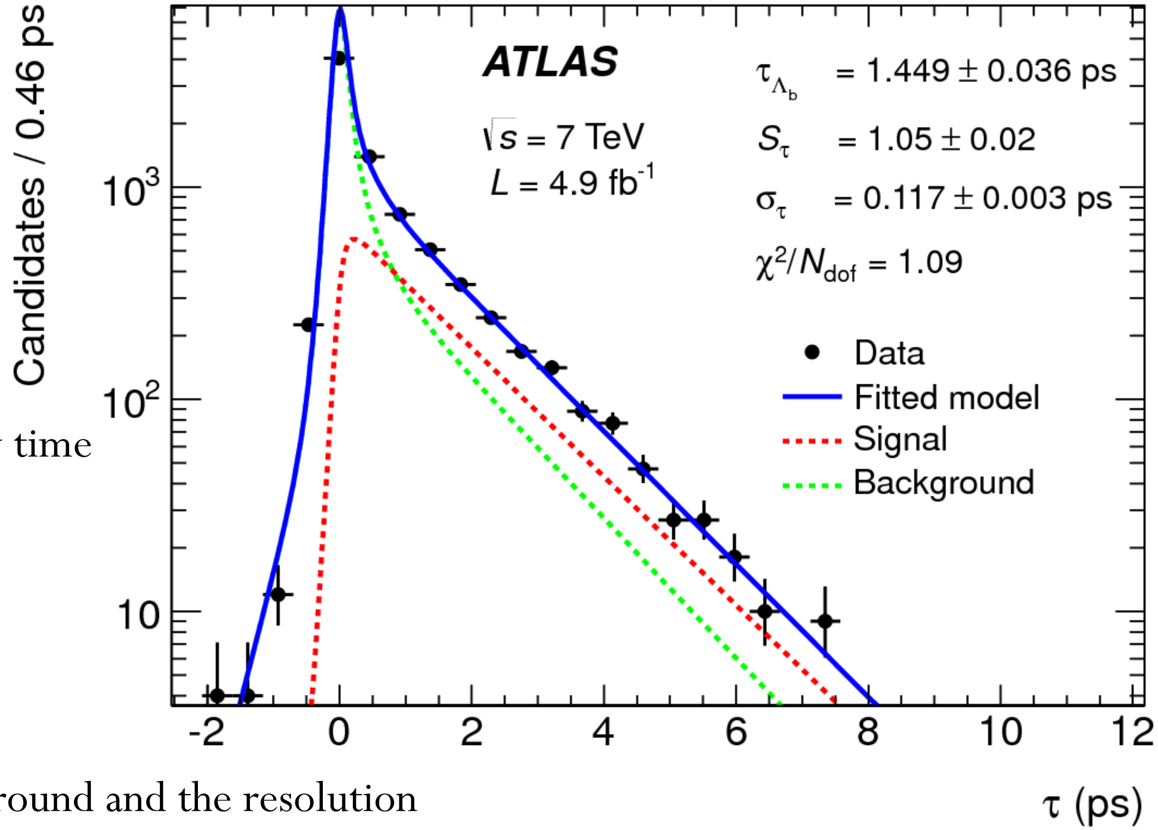
Lifetime measurement - III

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:

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

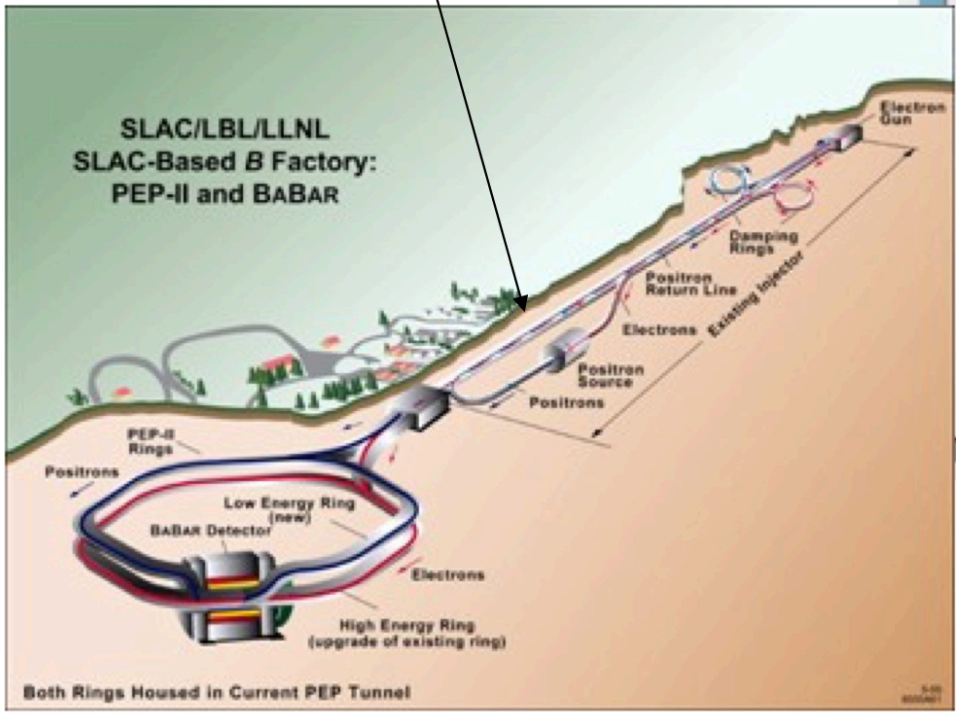


The fit takes into account the background and the resolution

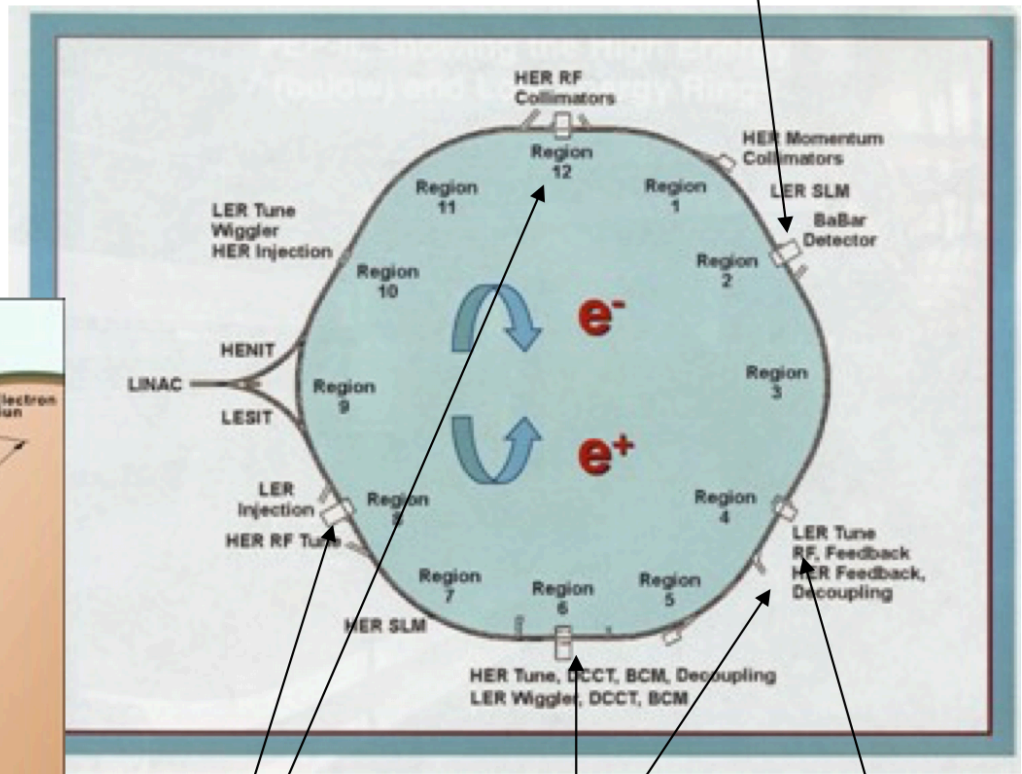
Typical resolutions: O(10^{-13} s) ➔ tens of μm

PEP-II e^+e^- Collider

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



BaBar Detector



HER
RF
476 MHz

Feedbacks
Diagnostics

LER
RF
476 MHz

C = 2200 m

3.1 GeV positrons x 9 GeV electrons

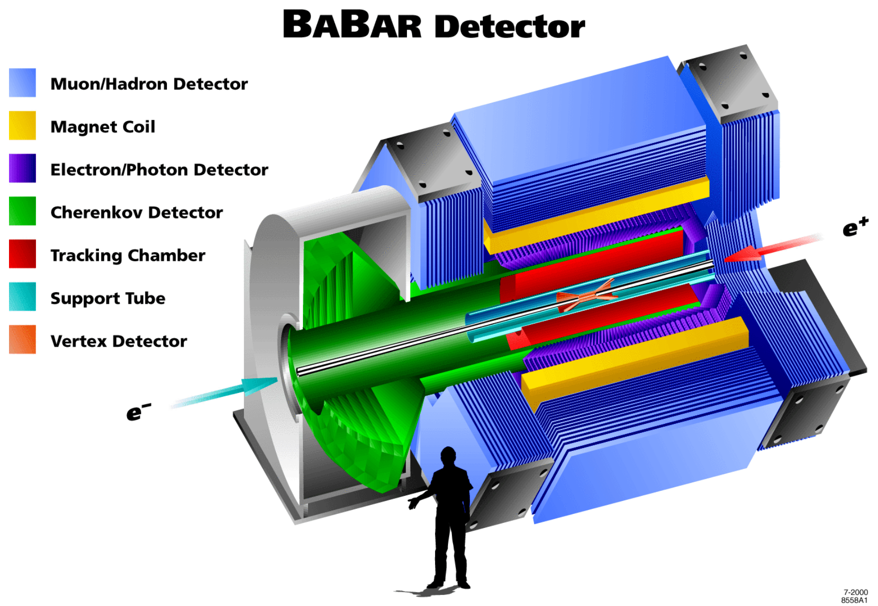
B-factories

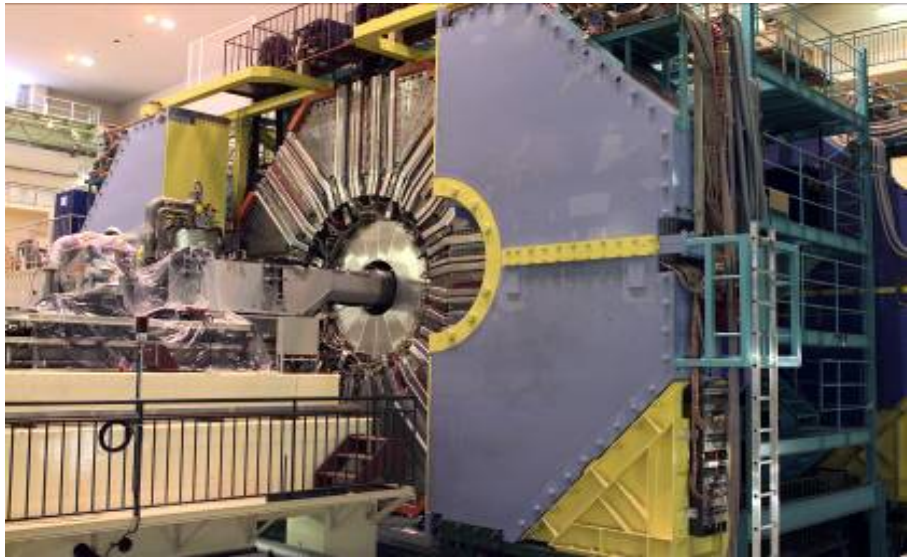
BABAR @ PEP-II

collected L=557 fb^{-1}

BELLE @ KEKB

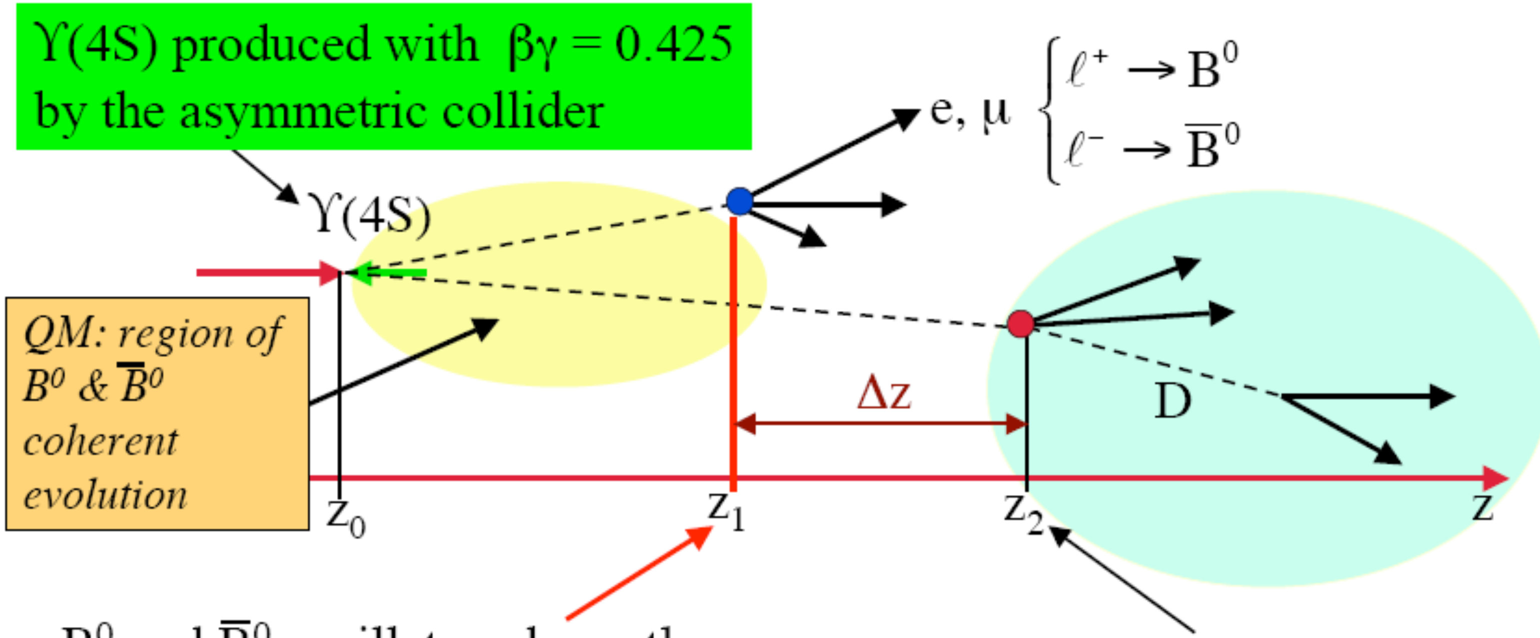
collected L=1040 fb^{-1}





Correlated B meson pairs

B



B^0 and $\overline{B}^0$ 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)

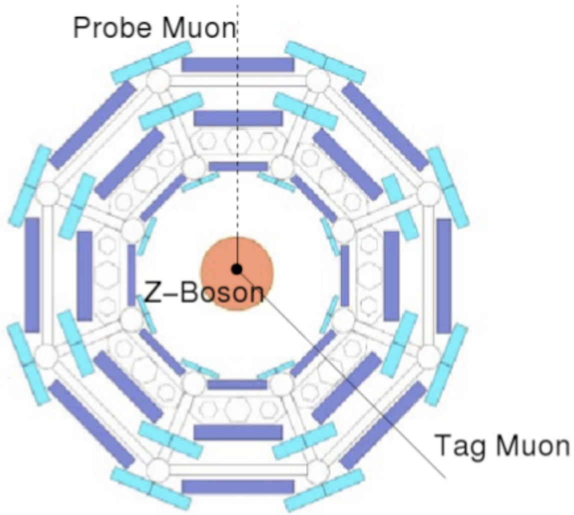
Efficiency measurement - II

- Measure single muon efficiencies as a function of kinematics (p_T, η, …); eventually 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.

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

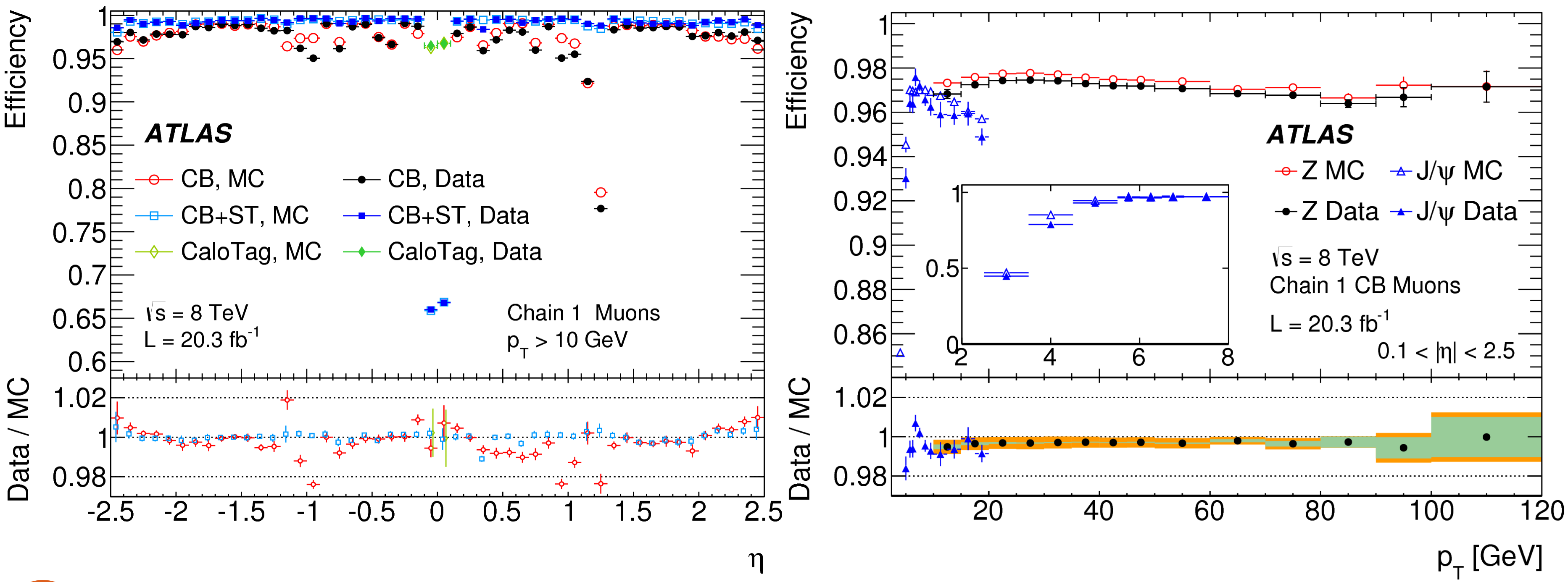
T&P: a "Tag Muon" in the MS and a "Probe" in the ID
Tag+Probe Inv.Mass consistent With a Z boson
➔ There should be a track in the MS

$$\varepsilon_{TP} = \frac{\#\mu - reco}{\#\mu - \mathrm{exp}ected}$$



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.

Exercise:

Determine the tracking efficiency for charged pions as a function of momentum in the KLOE detector exploiting the decay:

$\phi \to \pi^+\pi^-\pi^0$

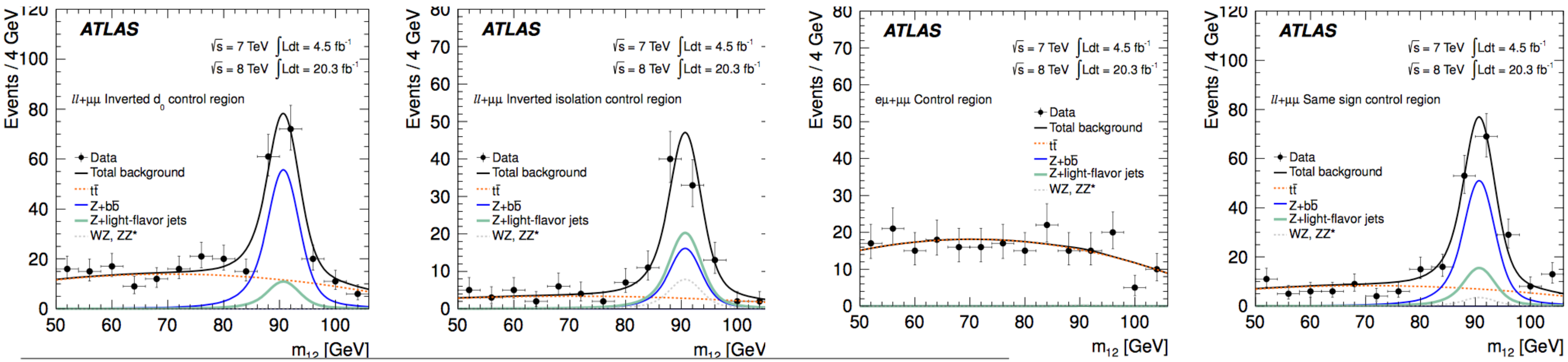
Background measurement - I

- 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	$9.2 \pm 1.3\%$	$39.3 \pm 2.6\%$	$0.0 \pm 0.8\%$	$16.9 \pm 1.6\%$
$t\bar{t}$	$58.0 \pm 0.9\%$	$34.2 \pm 1.6\%$	$99.7 \pm 1.0\%$	$52.5 \pm 1.1\%$



(d)

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 $m_{\text{min}} < m_{34} < 115$ GeV, where m_{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

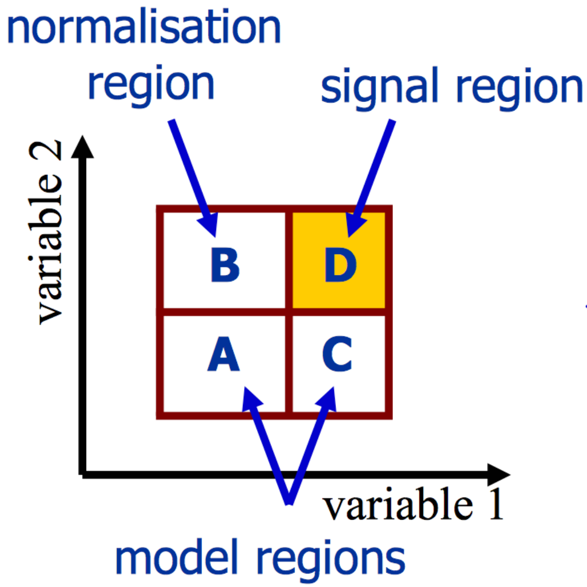
For the background, due to the independence we have few relations:

$$B/D = A/C$$

$$B/A = D/C$$

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

$$D = CB/A$$



Luminosity measurement - I

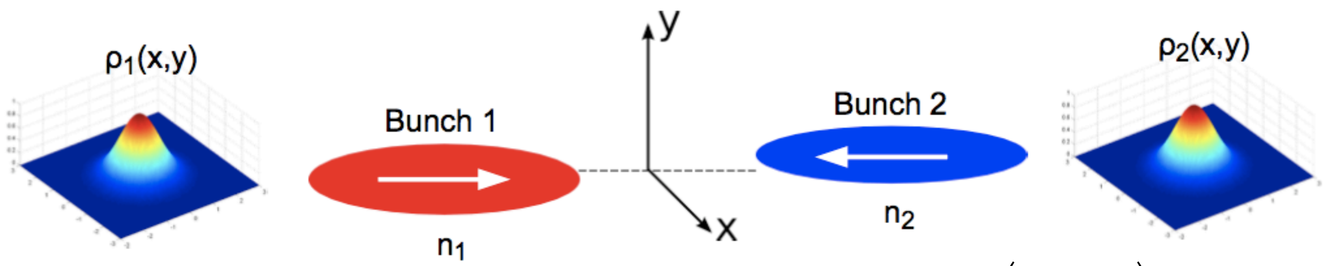
- In order to get the luminosity we need to know the "cross-section" of a candle process:

$$L = \frac{\dot{N}}{\sigma}$$

- In e^+e^- experiments QED helps, since Bhabha scattering can be theoretically evaluated with high precision (< 1%).
- In pp experiment the situation is more difficult.
  - Two-step procedure: continuous "relative luminosity" measurement through several monitors. Count the number of "inelastic interactions";
  - time-to-time using the "Van der Meer" scan the absolute calibration is obtained by measuring the effective σ_{inel}.

Luminosity measurement - II

Van der Meer scan: Measurement of the rate of inelastic interactions as a function of the bunch horizontal and vertical separations:



$$R(\delta x) = \int \rho_1(x,y)\rho_2(x+\delta x,y)\,dx\,dy \propto \exp\left(-\frac{\delta x^2}{2\Sigma_x^2}\right)$$

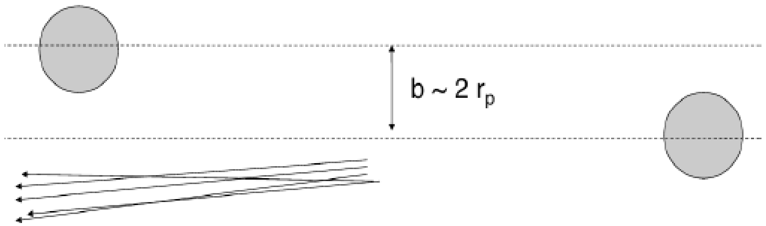
➔Determine the transverse bunch dimensions Σ_x, Σ_y and the inelastic rate at 0 separation.
➔Using the known values of the number of protons per bunch from LHC monitors, one get the ***inelastic cross-section*** that provides the absolute normalization.

$$L = n_b f \frac{N_1 N_2}{4\pi\Sigma_x\Sigma_y} = \frac{\dot{N}_{inel}}{\sigma_{inel}}$$

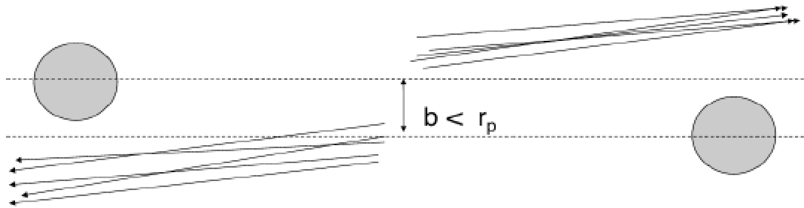
$$\sigma_{inel} = \left(\frac{\dot{N}^0_{inel}}{n_b f}\right)\frac{4\pi\Sigma_x\Sigma_y}{N_1 N_2}$$

sezione d'urto grande ⟶ processo ad alta rate ($R = L\sigma$) ⟶ alta statistica

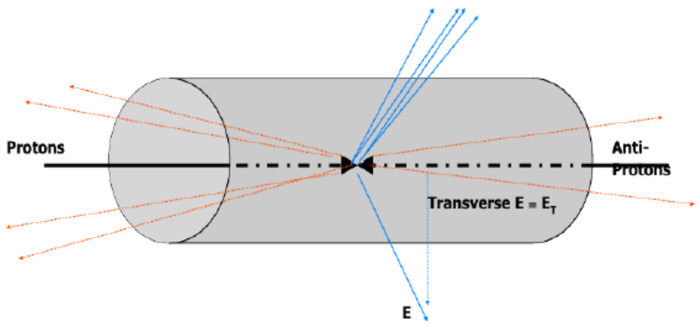
Processo utilizzato: **scattering inelastico** pp ($\sigma \sim 100mb$)



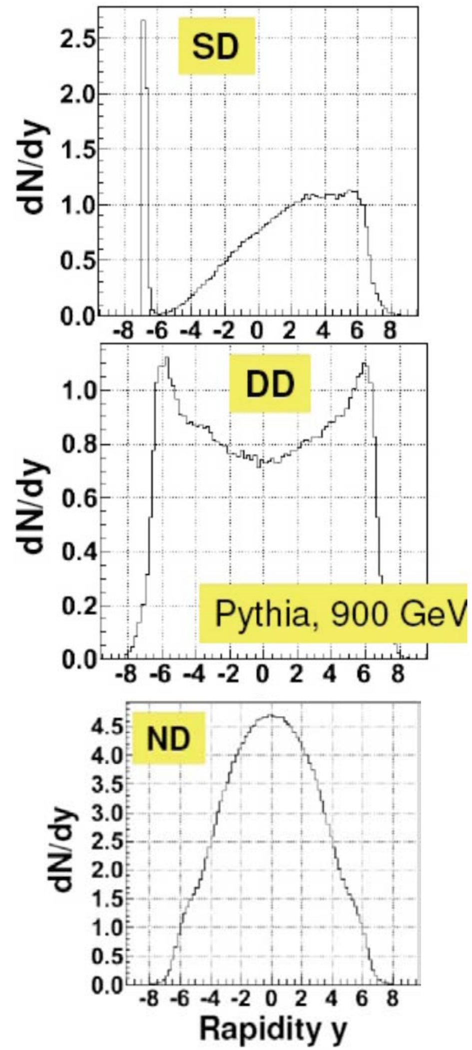
- Single Diffractive

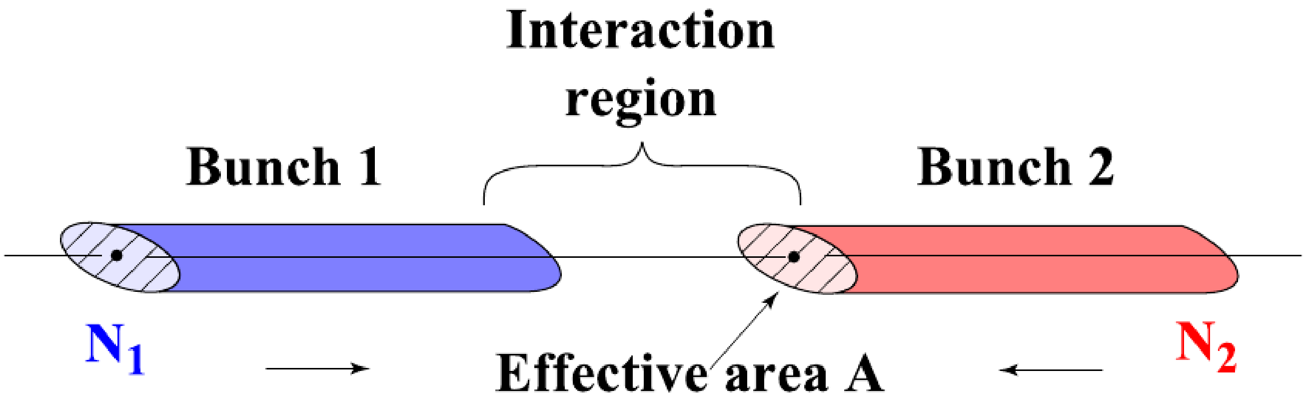


- Double Diffractive



- Non diffractive




Interaction region
Bunch 1
Bunch 2
N1
N2
Effective area A

Recap

- Let's remind at this point that our aim is to learn how to design an experiment.
- We have seen:
  - Definition of the process we want to study
  - Selection of the events correponding to this process
  - Measurement of the quantities related to the process
  - Other measurements related to the physics objects we are studying.
- Now, in order to really design an experiment we need:
  - To see how projectiles and targets can be set-up
  - To see how to put together different detectors to mesure what we need to measure