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Precise luminosity measurement using electroweak
bosons and two photon dimuon production with
LHCb

Francesco De Lorenzi for LHCb collaboration

Outline

- ▶ LHCb experiment
- ▶ What is luminosity
- ▶ How we measure it
- ▶ Electroweak bosons rapidity distributions
- ▶ Two photon dimuon production

LHCb experiment

- ▶ LHCb is a b-physics dedicated experiment using the 14 TeV LHC beam
- ▶ Nominal Luminosity $2 \cdot 10^{32} \text{ cm}^{-2}\text{s}^{-1}$ ($\sim 2 \text{ fb}^{-1} / \text{year}$)
- ▶ Pseudorapidity range $1.9 < \eta < 4.9$
 - ▶ $1.9 < \eta < 2.5$ overlap with ATLAS/CMS ($|\eta| < 2.5$)
 - ▶ Unique $\eta > 2.5$
- ▶ Possible to trigger and reconstruct low p muons
 - ▶ $P > 6 \text{ GeV}$
 - ▶ $P_t > 1 \text{ GeV}$

LHCb experiment

LHCb experiment

Vertex Locator

LHCb experiment

RICH - Particle identification

LHCb experiment

Tracking System

LHCb experiment

Calorimeters

LHCb experiment

Muon Detector

Luminosity

- ▶ Luminosity is the proportionality factor that relates number events recorded of a particular process and the cross-section of the process

$$\begin{array}{ccccc} \text{Experimental} & & & & \text{\# events} \\ \text{efficiency} & \longrightarrow & \mathcal{E}_X \sigma_X L = N_X & \longleftarrow & \text{recorded} \\ & \nearrow & & \nwarrow & \\ & \text{Cross-section} & & \text{Luminosity} & \end{array}$$

- ▶ It is an accelerator parameter that depends on the beam shape and dimensions

$$\begin{array}{ccccc} & & \text{\# particles in} & & \\ & & \text{the bunches} & & \\ & & \downarrow & & \\ & & n_1 n_2 & & \\ L = \int f \frac{}{4\pi\sigma_x\sigma_y} dt & & & & \text{Transverse} \\ \uparrow & & & \longleftarrow & \text{beam profiles} \\ \text{Collision frequency} & & & & \end{array}$$

How to measure the Luminosity?

- ▶ Direct estimation: measure beam parameters
 - ▶ Van der Meer Scan 10% accuracy
 - ▶ Study of Beam-Gas interaction in Vertex detector
(M. Ferro-Luzzi, CERN-PH-EP-2005-023)
- ▶ Indirect estimation: measure the rate for a “high precision predicted” process:

$$L = \frac{N_X}{\epsilon_X \sigma_X}$$

- ▶ $W^\pm$ and Z production (using rapidity distributions)
 - ▶ Model-dependent theoretical uncertainty due to PDFs (2-3%)
- ▶ Elastic two photon di-muon production
 - ▶ ~0.4% theoretical uncertainty

Z and $W^\pm$ rapidity distributions

Eigenvectors approach: MSTW08

Neural Network approach: NNPDF1.0

Z & W $\pm$

$$\sigma_X = \int dx_a dx_b \underbrace{f(x_a, Q^2) f(x_b, Q^2)}_{\text{PDFs}} \underbrace{\sigma_{ab \rightarrow X}(x_a, x_b, Q^2)}_{\text{Partonic Cross-Section}}$$

2-3% accurate (W $\pm$ & Z) ~1% accurate

MSTW08 PDF structure

- ▶ MSTW08 PDF set is arranged in:
 - ▶ Central value (best fit)
 - ▶ 20 linearly independent eigenvectors Q_i
 - ▶ $Q_i \pm 1\sigma$ (40 Error sets)
- ▶ Can generate distributions using the “*best-fit*” or any of the $\pm 1\sigma$ error sets.
- ▶ Then any distribution $f(y) = d\sigma/dy$ is a linear combination of the best-fit and eigenvector distributions

$$f(y) = f_0(y) + \sum_{i=1}^{20} W_i^+ \sigma_i^+(y) + \sum_{i=1}^{20} W_i^- \sigma_i^-(y) \quad \sigma_i^\pm(y) = f_0(y) - f_i(y)$$

Where W_i are gaussian number Gauss (0,1)

Pseudo-experiment Generation

Generated Z & Ws in 1000 toy experiment considering:

- ▶ y distribution as linear combination of eigenvectors using Gaussian weight: $W_i = \text{Gauss}(0, 1)$
- ▶ Statistical smearing in each bin
- ▶ LHCb acceptance and trigger and reco efficiency (see S. Traynor's talk)
- ▶ Integrated luminosity tested
 - ▶ 0.1 fb^{-1}
 - ▶ 1 fb^{-1}
 - ▶ 10 fb^{-1}

Fit algorithm

- ▶ Given we have some data with an unknown composition, can we fit for eigenvectors? Try:

$$f(y) = \lambda_0 \left(f_0(y) + \sum_{i=1}^{20} \lambda_i^+ \sigma_i^+(y) + \sum_{i=1}^{20} \lambda_i^- \sigma_i^-(y) \right)$$

Overall normalization:
LUMINOSITY

PDF weight

- ▶ Minimizing the χ^2 (constraining to the current knowledge of pdf)

$$\chi^2 = \sum_{bin} \frac{N_{bin} - \lambda_0(f_0 + \sum \lambda_i \sigma_i^+)}{\delta_{bin}} + \sum_{i>0} \lambda_i^2$$

- ▶ Considering symmetric $+1\sigma$ and -1σ (21 parameters)

NNPDF1.0

- ▶ **Completely different from other PDF set**
 - ▶ Monte Carlo approach with neural networks
 - ▶ Robust error estimation
 - ▶ Organized in MC replicas of the PDF
 - ▶ Event generation through any of the replicas

Best estimation for any functional $F[q]$ of the PDF set is obtained as average over the MC-replicas

$$\langle F[q] \rangle = \frac{1}{N_{rep}} \sum_{k=1}^{N_{rep}} F[q^{(k)}]$$

And its uncertainty as RMS

$$\sigma_F = \left(\frac{1}{N_{rep} - 1} \sum_{k=1}^{N_{rep}} \left(F[q^{(k)}] - \langle F[q] \rangle \right)^2 \right)^{1/2}$$

Fit algorithm

- ▶ Given a rapidity distribution I fit this distribution with:

- L_0^i is free parameter (Luminosity)

$$f = L_0^i \frac{d\sigma}{dy}(i)$$

- $\frac{d\sigma}{dy}(i)$ is the rapidity distribution generated with replica #i
- For $1 \leq i \leq 1000$

- ▶ If χ^2 probability is $> 1\%$ then record the value of L_0^i
- ▶ Best estimate for luminosity is the mean value of the estimate luminosity
- ▶ Uncertainty on luminosity is RMS

Test of the algorithm

- ▶ Generation of 1000 rapidity distributions
- ▶ 500 considered as “pseudo-data”
 - ▶ LHCb acceptance and trigger and reco efficiency
 - ▶ Integrated luminosity tested
 - ▶ 0.1 fb^{-1}
 - ▶ 1 fb^{-1}
 - ▶ 10 fb^{-1}
- ▶ 500 considered as theory distributions

Fitting each of 500 pseudo-data with each of the 500 theory distributions to understand the precision that it is possible to reach with this method

Summary - Precision achieved

	0.1 fb ⁻¹			
	MSTW08	CTEQ66	Alekhin	NNPDF
W+	1.8	2.4	2.0	2.9
W-	1.9	2.6	2.2	2.7
Z	1.9	2.4	2.2	2.4
WWZ	1.7	2.3	1.8	2.0
	1 fb ⁻¹			
	MSTW08	CTEQ66	Alekhin	NNPDF
W+	1.6	2.2	1.8	2.4
W-	1.6	2.3	2.1	2.4
Z	1.7	2.1	1.9	1.8
WWZ	1.3	2.1	1.4	2.2
	10 fb ⁻¹			
	MSTW08	CTEQ66	Alekhin	NNPDF
W+	1.3	2.0	1.5	2.5
W-	1.2	1.9	1.6	3.0
Z	1.4	1.9	1.9	1.9
WWZ	0.8	1.7	1.0	-

Percentage statistical uncertainty on fitted luminosity

Precision doesn't scale with $\frac{1}{\sqrt{N_{\text{events}}}}$

Model dependence

- ▶ Different models predict different cross-sections and so different estimates of the luminosity
- ▶ Selecting only good fits with χ^2 probability $> 1\%$ allow to consider consistent models
- ▶ Reduce systematic uncertainty due to model dependence

	0.1 fb ⁻¹		
	CTEQ66	Alekhin	NNPDF
W ⁺	-3.2	-3.7	5.0
W ⁻	0.1	-2.0	-1.5
Z	-1.4	-5.6	3.4
WWZ	-0.7	-3.6	5.0

Percentage bias on fitted luminosity respect MSTW08

Elastic di-muon production

CERN-THESIS-2009-020

Francesco De Lorenzi

Di-muon elastic production

$$p + p \rightarrow p + p + \mu^+ + \mu^-$$

- ▶ Cross-section theoretically known better than 1%
- ▶ Cross-section is $\sim 69\text{pb}$ inside LHCb
- ▶ Clear signature for signal/background discrimination

Trigger & Selection

- ▶ LHCb luminosity trigger
 - ▶ Low multiplicity in the event
 - ▶ Invariant mass $> 2 \text{ GeV}$

- ▶ Offline selection requires:
 - ▶ Di-muon mass $2 \text{ GeV} < M < 20 \text{ GeV}$
 - ▶ Di-muon $P_t < 50 \text{ MeV}$

17% efficiency

Of the events with 2 muons
in LHCb acceptance

$\sim 1200 \text{ events in } 100 \text{ pb}^{-1}$

Background processes

► Inelastic di-muon production

- Break up of one or both protons
- Cross-section in LHCb ~ 60 pb
- Uncertainty $\sim 35\%$

► Di-muon production via double pomeron exchange (DPE)

- Pomerons: multiple gluon emission
- Cross-section in LHCb ~ 100 pb
- Dominant background
- Uncertainty $\sim 50\%$

► Standard model process

- Drell-Yan
- Heavy quark semi-leptonic decays

► Pion/Kaon mis-id as muons

Invariant Mass

Full detector
sim

Full detector
sim

Generator Level

Generator Level

Di-muon Pt

Full detector
sim

Full detector
sim

Generator Level

Generator Level

Summary

- ▶ Z and Ws rapidity distribution fit allow to achieve a precision on the measurement of the luminosity of:
 - ▶ 1.6% for 0.1 fb^{-1}
 - ▶ 1.3% for 1 fb^{-1}
 - ▶ 0.8% for 10 fb^{-1}
- ▶ Elastic di-muon production
 - ▶ Selecting candidates with 17% efficiency and 96% purity
 - ▶ 3% for 0.1 fb^{-1}
 - ▶ 1% for 1 fb^{-1}
- ▶ Fully systematics study ongoing (detector efficiency etc.)

How precision scales