

Experimental Physics at Hadron Colliders CERN Summer Students Lectures, July 17-21, 2023 - Lecture 2/4

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Work Plans

Lecture 1: Introduction, fundamentals, cross sections

Lecture 2: Standard model measurements

Lecture 3: Higgs physics

Lecture 4: Searches for new physics

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Data and Analysis Chain

Detector









Software & Computing

LHC computing scale

- ~1 million cores fully occupied
- ~1 EB (~500 PB disk, > 500 PB tape)
- Global networking (~10-100Gbps)
- ~140 Computing centres in 33 countries

Challenges

- Increasing data volume and complexity
- Maintenance
- Opportunities
 - Heterogeneous computing resources
 - Applications of machine learning
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An ultra-compressed deep neural network on a field-programmable gate array. (Image: Sioni P. Summers)

Institute of Experimental Particle Physics (ETP)





What do we actually reconstruct from collisions?









What do we actually reconstruct from collisions?

- Energy and momenta of "stable" particles
 - Electrons, positrons, muons, anti-muons, charged hadrons
 - Photons, neutral hadrons
- Identify particle species
 - Including reconstruction of "unstable" particles from decay products
- Assign proton-proton collisions (pile-up removal)









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Jet History

Di-jet events with clearly separated energy depositions

- "Jet algorithm" based on cell structure of calorimeters (UA1 & UA2)
- UA1 later also used a cone algorithm with





(ref. [6]) uses $\Lambda = 0.5$ GeV while $\Lambda = 0.15$ GeV would bring the calculated rates in better agreement with the data. Howfrom the data [13]. UA2, PLB 118 (1982).



- Primary goal is to find correspondence between
 - Detector measurements
 - Particles in final state
 - Hard partons
- Classes of algorithms
 - Cone algorithms
 - Sequential recombination
- Requirements
 - Infrared and collinear safe
 - Order independence
 - Ease of implementation
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IR unsafe: Sensitive to the addition of soft particles



Coll. unsafe: Sensitive to the splitting of a 4-vector (seeds!)



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Anti-kT algorithm













$$d_{ij} = \min(k_{ti}^{2p}, k_{tj}^{2p}) \frac{\Delta R_i^2}{R^2}$$
$$d_{iB} = k_{ti}^{2p},$$

p=-1 anti- k_T algorithm p=0 Cambridge/Aachen p=1 k_T algorithm





Event rates at the LHC

Total cross sections

~1.6*10⁹ /s (80mb, 2*10³⁴cm⁻²s⁻¹)

- Bunch crossing rate of 40MHz
- Jets (E_T^{jet} > 100 GeV)
- ~40000 Hz
- W & Z bosons
 - ~4000 Hz, ~1000 Hz
- Top Quarks
- ~20 Hz
 Jets (E_T^{jet} > 650 GeV)
 ~6 Hz
 - Higgs bosons
 - ~1 Hz (50pb, 2*10³⁴cm⁻²s⁻¹)







Why are these jet cross sections so large?

PDFs

Coupling is "stronger"







Strong interaction





Strong interaction

Theory

- Some contributions lead to divergences, e.g. quark self-energy
- These infinities can be reabsorbed in the definitions of fields and parameters, e.g. couplings and masses
- Described by renormalisation group equa
- Running of coupling at leading order
- **Consequence:**
 - $Q^2 \rightarrow 0$? Can not be answered with per
 - Q² large. Strong coupling becomes weak. Asymptotic freedom. Perturbation theory works.







ation (RGE)

$$\begin{aligned} \alpha_s(Q^2) &= \frac{\alpha_s(\mu^2)}{1 + \alpha_s(\mu^2)\beta_0 \ln\left(\frac{Q^2}{\mu^2}\right)} \\ \alpha_s(Q^2) &= \frac{1}{\beta_0 \ln\left(\frac{Q^2}{\Lambda^2}\right)} \end{aligned} \qquad \beta_0 = \frac{33 - 2 \cdot R}{12\pi} \end{aligned}$$
rturbation theory







Inclusive Jet Cross Sections

- Abundant production of jets
- Large dynamic range to study α_s

As a function of jet transverse momentum in bins of rapidity (up to |y| = 4.7!)





20 GeV up to > 2TeV (central) • JES 2-4%

NLO pQCD describes data over 14 orders of magnitude!

Constraints on gluon PDFs





Inclusive Jets: α_s





X^{2} fit of $\alpha_{s}(M_{z})$ for all jet p_{T} and |y| bins - In fit: all exp. + PDF + NP uncertainties - PDFs: CT10 NLO PDF sets for various $\alpha_{s}(M_{z})$ 19.7 fb⁻¹ (8TeV) CMS 200 • $\chi^2[\alpha_s(M_7)]$ - Polynomial Fit $\overline{\alpha_{\rm S}}({\rm M_Z}) = 0.1164^{+0.0029}_{-0.0032}$ 195 $(\mu_{\rm B}/\mu, \, \mu_{\rm F}/\mu) = (1, \, 1)$ χ^2 $\chi^2_{min}/N_{Bins} = 186.5/185$ 190-0.113 0.116 0.119 0.123 0.127 $\alpha_{S}(M_{7})$



2-jet 3-jet Ratio





√s [TeV]	lum [fb⁻¹]	α _s (M _z)	exp NP PDF	scale
7	5.0	0.1148	23	50
8	19.7	0.1150	22	+50



Measurement of α_s



Physics of the W and Z Boson

- "Standard candle" for calibrations and PDFs
- Testing QCD
- W boson mass measurement
- Asymmetries and weak mixing angle
- Triple and quartic gauge couplings

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W boson mass measurement

Observables

- Lepton transverse momentum
- Transverse missing energy
- $M_{\rm T}^2 = 2 \, p_{\rm T}(\ell) p_{\rm T}(\nu) \, (1 \ell) \, \ell$ Transverse mass
- Challenges
 - Experimental: lepton energy scale; missing transverse energy; pile-up conditions
 - Theoretical: W transverse momentum; PDFs
- Strategy (ATLAS)
 - Exploit lepton transverse momentum and transverse mass

$$-\cos\Delta\phi(\ell,
u))$$

W boson mass measurement

Results

Tension in experiment results!

Are Standard Model measurements consistent?

Multi-Boson Production

Di-Boson Production

- Large number of processes study
- Generally good agreement between experiment and theory
- Constraint on anomalous couplings

May 2021		CMS	S Prel
CMS measurements vs. NNLO (NLO) theory	7 TeV CMS 8 TeV CMS	6 measurement (stat,stat+sys) 6 measurement (stat,stat+sys)	,) ⊢+-) ⊢+
	13 TeV CM	IS measurement (stat,stat+sy	s) 🛏
γγ	⊢−−−− +O −−−−−− 1	$1.06 \pm 0.01 \pm 0.12$	5.0 f
$W\gamma$, (NLO th.)	► ► 	$1.16 \pm 0.03 \pm 0.13$	5.0 f
$W\gamma$, (NLO th.)	⊢	$1.01 \pm 0.00 \pm 0.05$	137 ·
$Z\gamma$, (NLO th.)	k <mark>−+o+−−</mark> t	$0.98 \pm 0.01 \pm 0.05$	5.0 f
$Z\gamma$, (NLO th.)		$0.98 \pm 0.01 \pm 0.05$	19.5
WW+WZ	⊬ o <mark></mark> I	$1.01 \pm 0.13 \pm 0.14$	4.9 f
WW	⊦ <mark></mark> ⊦	$1.07 \pm 0.04 \pm 0.09$	4.9 f
WW	⊢⊦●¦ I	$1.00 \pm 0.02 \pm 0.08$	19.4
WW	⊢ <mark>+o+</mark> I	$1.00 \pm 0.01 \pm 0.06$	35.9
WZ	⊢+ <mark></mark> -o+-I	$1.05 \pm 0.07 \pm 0.06$	4.9 f
WZ	⊢	$1.02 \pm 0.04 \pm 0.07$	19.6
WZ	⊢ <mark>⊹●∔</mark> ⊣	$1.00 \pm 0.02 \pm 0.03$	137
ZZ	H	$0.97 \pm 0.13 \pm 0.07$	4.9 f
ZZ	⊢ ; ● ;	$0.97 \pm 0.06 \pm 0.08$	19.6
ZZ	<mark>⊢∔</mark> ●∔→↓	$1.04 \pm 0.02 \pm 0.04$	137
0.5 All results at:	¹ Production Cr	ross Section Ratio:	σ_{exp}

Multi-Boson Production

Tri-Boson Production

Observed WWW and WWy processes

Observation of three massive gauge bosons (W or Z) (CMS result number 1000!)

Vector Boson Scattering

Electroweak production of same-sign W-pairs

Vector Boson Scattering

- Important process to check EW physics, probing at high energies
- W/o the Higgs Boson amplitudes violate unitarity
- Processes clearly observed. Extracting contribution from polarised W bosons

Multiboson production overview

		Wγ	7 TeV	PRD 89 (2014) 092005			
		Wγ	13 TeV	PRL 126 252002 (2021)			
		Zγ	7 TeV	PRD 89 (2014) 092005			
		Zγ	8 TeV	JHEP 04 (2015) 164			
		ww	7 TeV	EPJC 73 (2013) 2610			
	lo	ww	8 TeV	EPJC 76 (2016) 401			
	305	ww	13 TeV	PRD 102 092001 (2020)			
		WZ	7 TeV	EPJC 77 (2017) 236			
	, v	WZ	8 TeV	EPJC 77 (2017) 236			
		WZ	13 TeV	JHEP 07 (2022) 032			
		ZZ	7 TeV	JHEP 01 (2013) 063			
		ZZ	8 TeV	PLB 740 (2015) 250			
		ZZ	13 TeV	EPJC 81 (2021) 200			
		VVV	13 TeV	PRL 125 151802 (2020)			
		www	13 TeV	PRL 125 151802 (2020)			
		WWZ	13 TeV	PRL 125 151802 (2020)			
		WZZ	13 TeV	PRL 125 151802 (2020)			
	Lo Lo	ZZZ	13 TeV	PRL 125 151802 (2020)			
	305	WVγ	8 TeV	PRD 90 032008 (2014)			
	문	WWγ	13 TeV	SMP-22-006			$\sigma(WW\gamma) =$
	+	WYY	8 TeV	JHEP 10 (2017) 072			$\sigma(W\gamma\gamma)=4$
		WYY	13 TeV	JHEP 10 (2021) 174			
		Ζγγ	8 TeV	JHEP 10 (2017) 072			σ
		Ζγγ	13 TeV	JHEP 10 (2021) 174		-	$\sigma(Z\gamma\gamma) = 5.4$
		VBF W	8 TeV	JHEP 11 (2016) 147			
		VBF W	13 TeV	EPJC 80 (2020) 43			
		VBF Z	7 TeV	JHEP 10 (2013) 101			
		VBF Z	8 TeV	EPJC 75 (2015) 66			
		VBF Z	13 TeV	EPJC 78 (2018) 589			
	Ś	EW WV	13 TeV	PLB 834 (2022) 137438			
	8	ex. $\gamma\gamma \rightarrow WV$	W8 TeV	JHEP 08 (2016) 119			-
	P	EW qqW γ	8 TeV	JHEP 06 (2017) 106			
	a	EW qqW γ	13 TeV	Accepted by PRD			-
	8	EW os WW	13 TeV	Submitted to PLB			- σ(EV
	>	EW ss WW	8 TeV	PRL 114 051801 (2015)			$\sigma(EW ss W)$
		EW ss WW	13 TeV	PRL 120 081801 (2018)		σ(Ε	W ss WW) = 4
		EW qqZ γ	8 TeV	PLB 770 (2017) 380		σ(EW qc	$(Z\gamma) = 1.9 \text{ fb}$
		EW qqZ γ	13 TeV	PRD 104 072001 (2021)			σ (EW qqZ γ) =
		EW qqWZ	13 TeV	PLB 809 (2020) 135710		σ(EW qqWZ	.) = 1.8 fb
		EW qqZZ	13 TeV	PLB 812 (2020) 135992	-	$\sigma(\text{EW qqZZ}) = 0.33 \text{ fb}$	
				1.0	e-01	1	.0e+01

Top Physics

- Heaviest known elementary particle
- Couples with a strength of 1 to the Higgs field

$$y_t = \frac{\sqrt{2}m_t}{v} \sim 1$$

- Predicted to explain CP violation in Kaon system (1973)
- Discovery by CDF and D0 at the Tevatron (1994)
- Decay into a W boson and a b quark
- Top quark decays before it hadronises
- Production at the LHC:

Top Physics Single top production cross sections

Top Physics

Top mass measurements

ATLAS+CMS Preliminary	m _{top} summary,√s = 7-13 TeV Oct 2022				
World comb. (Mar 2014) [2]	total stat				
total uncertainty					
HC comb (Sen 2013) Hetopwe Hit	$m_{top} \pm total (stat \pm syst)$ (s Ref. 173 29 + 0.95 (0.35 + 0.88) 7 ToV (11)				
World comb (Mar 2014) $H = H$	$173.23 \pm 0.35 (0.35 \pm 0.66)$ 7 TeV [1] $173.34 \pm 0.76 (0.36 \pm 0.67)$ 1 96-7 TeV [2]				
ATLAS I+iets	$172.33 \pm 1.27 (0.75 \pm 1.02)$ 7 TeV [2]				
ATLAS, dilepton	$-173.79 \pm 1.41 (0.54 \pm 1.30) \qquad 7 \text{ TeV [3]}$				
ATLAS, all iets	175.1± 1.8 (1.4± 1.2) 7 TeV [4]				
ATLAS, single top	172.2±2.1 (0.7±2.0) 8 TeV [5]				
ATLAS, dilepton	172.99±0.85 (0.41±0.74) 8 TeV [6]				
ATLAS, all jets	173.72±1.15 (0.55±1.01) 8 TeV [7]				
ATLAS, I+jets	172.08±0.91 (0.39±0.82) 8 TeV [8]				
ATLAS comb. (Oct 2018)	172.69 ± 0.48 (0.25 ± 0.41) 7+8 TeV [8]				
ATLAS, leptonic invariant mass	H 174.41±0.81 (0.39±0.66±0.25) 13 TeV [9]				
ATLAS, dilepton (*)	172.63±0.79 (0.20±0.67±0.37) 13 TeV [10]				
CMS, I+jets	173.49±1.06 (0.43±0.97) 7 TeV [11]				
CMS, dilepton	172.50±1.52 (0.43±1.46) 7 TeV [12]				
CMS, all jets	173.49± 1.41 (0.69± 1.23) 7 TeV [13]				
CMS, I+jets	172.35±0.51 (0.16±0.48) 8 TeV [14]				
CMS, dilepton	172.82± 1.23 (0.19± 1.22) 8 TeV [14]				
CMS, all jets	172.32±0.64 (0.25±0.59) 8 TeV [14]				
CMS, single top	172.95±1.22 (0.77±0.95) 8 TeV [15]				
CMS comb. (Sep 2015) ⊢ ⊭ ⊣	172.44 ± 0.48 (0.13 ± 0.47) 7+8 TeV [14]				
CMS, I+jets	172.25±0.63 (0.08±0.62) 13 TeV [16]				
CMS, dilepton	172.33±0.70 (0.14±0.69) 13 TeV [17]				
CMS, all jets	172.34±0.73 (0.20±0.70) 13 TeV [18]				
CMS, single top	172.13±0.77 (0.32±0.70) 13 TeV [19]				
CMS, I+jets (*)	171.77±0.38 13 TeV [20]				
CMS, boosted (*)	1/2./6±0.81 (0.22±0./8) [1] ATLAS-CONF-2013-102 [8] EPJC 79 (2019) 290 [15] EPJC 77 (2017) 354				
* Preliminary	[2] arXiv:1403.4427 [9] arXiv:2209.00583 [16] EPJC 78 (2018) 891 [3] EPJC 75 (2015) 330 [10] ATLAS-CONF-2022-058 [17] EPJC 79 (2019) 368				
	[4] EPJC 75 (2015) 158 [11] JHEP 12 (2012) 105 [18] EPJC 79 (2019) 313 [5] ATLAS-CONF-2014-055 [12] EPJC 72 (2012) 2202 [19] arXiv:2108.10407 [6] PLB 761 (2016) 350 [13] EPJC 74 (2014) 2758 [201 CMS-PAS_TOP-20_008				
	[7] JHEP 09 (2017) 118 [14] PRD 93 (2016) 072004 [21] CMS-PAS-TOP-21-012				
	75 100 105				
100 1/0 1	10 100 100				
m _{top} [GeV]					

Top Physics

 $\sigma_{t\bar{t}t\bar{t}}^{SM} = 12.0 \pm 2.4 \text{ fb}$

70,000 smaller than top pair production

Production of 4 top quarks; final state with 4 W bosons and 4 b quarks

/ 0.05

Events

Data / Pred.

Made possible by modern machine learning

Quiz

- Why is the jet (ET > 100 GeV) cross section larger that the cross section for W or Z boson production?
- Why are coupling constants not constant?
- How is vector boson scattering related to Higgs physics?
- How to we identify top quarks?
- What makes the top quark special?

References and further reading

Textbooks

- Modern Particle Physics by Mark Thomson
- QCD at Colliders by Ellis, Stirling, and Weber

Pictures

- CERN Document Server
- Wikipedia
- Or reference on page

References

- Previous CERN Summer Lectures https://indico.cern.ch/category/97/
- MIT's OCW 8.701 and 8.811
- KIT's Particle Physics master courses (you can contact me)
- Public results from ATLAS, CMS, and LHC combination groups
- Or reference on page
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