Course on Physics at the LH

Lecture/2

Introduction to collisions at LHC

LABORATÓRIO DE INSTRUMENTAÇÃO E FÍSICA EXPERIMENTAL DE PARTICULAS partículas e tecnologia Joao Varela Lisbon, PORTUGAL MARCH – MAY 2023

Introduction to collisions at LHC

- 1. Hadron interactions
- 2. QCD and parton densities
- 3. Monte Carlo generators
- 4. Luminosity and cross-section measurements
- 5. Minimum bias events
- 6. Jet physics

Hadron Interactions



Kinematical variables



Relevant kinematic variables:

- Transverse momentum: pT
- Rapidity: $y = \frac{1}{2} \cdot \ln (E p_z)/(E + p_z)$
- Pseudorapidity: $\eta = -\ln \tan \frac{1}{2}\theta$
- Azimuthal angle: ϕ



Proton-Proton Scattering



Example: Drell-Yan Process



QCD processes



Subprocess		$ \mathcal{M} ^2/g_s^4$	$ \mathcal{M}(90^{\circ}) ^{2}/g_{s}^{4}$
$\left.\begin{array}{c} qq' \to qq' \\ q\bar{q}' \to q\bar{q}' \end{array}\right\}$	$rac{4}{9} \; rac{\hat{s}^2 + \hat{u}^2}{\hat{t}^{2}}$	2.2	
$qq \rightarrow qq$	$\frac{4}{9}\left(\frac{\hat{s}^2+\hat{u}}{\hat{t}^2}\right.$	$\left(rac{\hat{s}^2 + \hat{t}^{2}}{\hat{u}^2} ight) - rac{8}{27} \; rac{\hat{s}^2}{\hat{u}\hat{t}}$	3.3
$q\bar{q} ightarrow q' \bar{q}'$	$\frac{4}{9} \; \frac{\hat{t}^{2} + \hat{u}^2}{\hat{s}^2}$		0.2
$q\bar{q} \to q\bar{q}$	$\frac{4}{9}\left(\frac{\hat{s}^2+\hat{u}}{\hat{t}^{2}}\right)$	$\left(rac{\hat{t}^{2} + \hat{u}^{2}}{\hat{s}^{2}} ight) - rac{8}{27} \; rac{\hat{u}^{2}}{\hat{s}\hat{t}}$	2.6
$q \overline{q} ightarrow g g$	$\frac{32}{27} \; \frac{\hat{u}^2 + \hat{t}}{\hat{u}\hat{t}}$	$\frac{2}{3} - \frac{8}{3} \; \frac{\hat{u}^2 + \hat{t}^2}{\hat{s}^2}$	1.0
$gg ightarrow q \overline{q}$	$rac{1}{6} \; rac{\hat{u}^2 + \hat{t}^{2}}{\hat{u}\hat{t}}$	$-rac{3}{8} \; rac{\hat{u}^2 + \hat{t}^{2}}{\hat{s}^2}$	0.1
qg ightarrow qg	$\frac{\hat{s}^2+\hat{u}^2}{\hat{t}^2}-$	$\frac{4}{9} \; \frac{\hat{s}^2 + \hat{u}^2}{\hat{u}\hat{s}}$	6.1
$gg \to gg$	$\frac{9}{4}\left(rac{\hat{s}^2+\hat{u}}{\hat{t}^2} ight)$	${{\hat r}^2 \over {\hat r}^2} + {{\hat s}^2 + {\hat t}^2 \over {\hat u}^2} + {{{\hat u}^2 + {\hat t}^2 \over {\hat s}^2}}$	+3) 30.4

Proton-Proton Scattering: final state



QCD & parton densities



Couse on Physics at the LHC

Lepton-proton scattering and proton structure



Structure Function





[see e.g. Halzen/Martin]

Scaling violation



Scaling violation

Proton quark dominated: $Q^2 \uparrow \Rightarrow F_2 \downarrow$ for fixed x Proton gluon dominated: $Q^2 \uparrow \Rightarrow F_2 \uparrow$ for fixed x



Q²-evolution described by DGLAP Equations

Couse on Physics at the LHC

Proton parton densities





Couse on Physics at the LHC

Monte Carlo Generators



Monte Carlo overview

Monte Carlo simulation ...

Numerical process generation based on random numbers

Method very powerful in particle physics

Event generation programs:

Pythia, Herwig, Isajet Sherpa ...

Hard partonic subprocess + fragmentation & hadronization ...

Detector simulation:

Geant ...

interaction & response of all produced particles ...

MC simulations in particle physics

Event Generator

simulate physics process (quantum mechanics: probabilities!)

Detector Simulation simulate interaction with detector material

Digitization

translate interactions with detector into realistic signals

Reconstruction/Analysis as for real data

Pythia sub-processes

No. Subprocess	No. Subprocess	No. Subprocess	No. Subprocess	No. Subprocess	No. Subprocess	No. Subprocess
Hard QCD processes:	$36 f_i \gamma \to f_k W^{\pm}$	New gauge bosons:	Higgs pairs:	Compositeness:	$210 f_i \overline{f}_j \to \tilde{\ell}_L \tilde{\nu}_\ell^* +$	$250 f_i g \to \tilde{q}_{iL} \tilde{\chi}_3$
11 $f_i f_j \rightarrow f_i f_j$	$69 \gamma\gamma \to W^+W^-$	141 $f_i \overline{f}_i \to \gamma/Z^0/Z'^0$	297 $f_i \overline{f}_j \to H^{\pm} h^0$	146 $e\gamma \rightarrow e^*$	211 $f_i \overline{f}_i \to \tilde{\tau}_1 \tilde{\nu}_{\tau}^* +$	$251 f_i g \to \tilde{q}_{iR} \tilde{\chi}_3$
12 $f_i \overline{f}_i \rightarrow f_k \overline{f}_k$	$70 \gamma W^{\pm} \to Z^0 W^{\pm}$	142 $f_i \overline{f}_i \to W'^+$	298 $f_i \overline{f}_i \rightarrow H^{\pm} H^0$	$147 dg \rightarrow d^*$	212 $f_i \overline{f}_i \to \tilde{\tau}_2 \tilde{\nu}_{\tau}^* +$	252 $f_i g \rightarrow \tilde{q}_{iL} \tilde{\chi}_4$
13 $f_i \overline{f}_i \rightarrow gg$	Prompt photons:	144 $f_i \overline{f}_i \to \mathbf{R}$	299 $f_i \overline{f}_i \rightarrow A^0 h^0$	$148 ug \rightarrow u^*$	213 $f_i \overline{f}_i \to \tilde{\nu}_\ell \tilde{\nu}_\ell^*$	253 $f_i g \to \tilde{q}_{iR} \tilde{\chi}_4$
$28 f_i g \rightarrow f_i g$	14 $f_i \overline{f}_i \rightarrow g\gamma$	Heavy SM Higgs:	$300 f_i \overline{f}_i \to A^0 H^0$	$167 \mathbf{q}_i \mathbf{q}_j \to \mathbf{d}^* \mathbf{q}_k$	214 $f_i \overline{f}_i \to \tilde{\nu}_{\tau} \tilde{\nu}_{\tau}^*$	$254 f_i g \to \tilde{q}_{jL} \tilde{\chi}_1^{\pm}$
53 gg $\rightarrow f_k \overline{f}_k$	18 $f_i \overline{f}_i \rightarrow \gamma \gamma$	$5 Z^0 Z^0 \rightarrow h^0$	$301 f_i \overline{f}_i \to H^+ H^-$	168 $q_i q_j \rightarrow u^* q_k$	216 $f_i \overline{f}_i \to \tilde{\chi}_1 \tilde{\chi}_1$	$256 f_i g \to \tilde{q}_{jL} \tilde{\chi}_2^{\pm}$
$68 gg \rightarrow gg$	$29 f_i g \rightarrow f_i \gamma$	$8 W^+W^- \rightarrow h^0$	Leptoquarks:	169 $q_i \overline{q}_i \to e^{\pm} e^{*\mp}$	$\begin{array}{ccc} 217 & f_i \overline{f}_i \rightarrow \tilde{\chi}_2 \tilde{\chi}_2 \\ \end{array}$	$258 f_i g \to \tilde{q}_{iL} \tilde{g}$
Soft QCD processes:	114 $gg \rightarrow \gamma\gamma$	71 $Z_{L}^{0}Z_{L}^{0} \rightarrow Z_{L}^{0}Z_{L}^{0}$	145 $q_i \ell_i \rightarrow L_0$	165 $f_i \overline{f}_i (\to \gamma^* / Z^0) \to f_k \overline{f}_k$	$\begin{array}{cccc} 211 & f_{i11} & \chi_2\chi_2 \\ 218 & f_{i}\overline{f}_{i} \rightarrow \tilde{\chi}_2\tilde{\chi}_2 \end{array}$	$259 f_i g \to \tilde{q}_i R \tilde{g}$
91 elastic scattering	$115 gg \to g\gamma$	72 $Z_{L}^{0}Z_{L}^{0} \rightarrow W_{L}^{+}W_{L}^{-}$	162 $qg \rightarrow \ell L_0$	166 $f_i \overline{f}_j (\to W^{\pm}) \to f_k \overline{f}_l$	$\begin{array}{cccc} 210 & f_{i}f_{i} & \chi_{3}\chi_{3} \\ 210 & f_{i}\overline{f}_{i} \rightarrow \tilde{\chi}_{i}\tilde{\chi}_{i} \end{array}$	$261 \mathbf{f}_i \mathbf{\bar{f}}_i \to \mathbf{\tilde{t}}_1 \mathbf{\tilde{t}}_1^*$
92 single diffraction (XB)	Deeply Inel. Scatt.:	73 $Z_{L}^{0}W_{L}^{\pm} \rightarrow Z_{L}^{0}W_{L}^{\pm}$	163 $gg \rightarrow L_0 \overline{L}_0$	Extra Dimensions:	$\begin{array}{c ccccccccccccccccccccccccccccccccccc$	$262 f_i \overline{f}_i \to \tilde{t}_2 \tilde{t}_2^*$
93 single diffraction (AX)	10 $f_i f_j \rightarrow f_k f_l$	76 $\tilde{W}_{I}^{+}\tilde{W}_{I}^{-} \rightarrow \tilde{Z}_{I}^{0}Z_{I}^{0}$	164 $q_i \overline{q}_i \rightarrow L_0 \overline{L}_0$	$391 f\overline{f} \to G^*$	$\begin{array}{c c} 220 & i_i i_i \rightarrow \chi_1 \chi_2 \\ 221 & f_i \overline{f}_i \rightarrow \tilde{\chi}_i \tilde{\chi}_2 \end{array}$	263 $f_i \overline{f}_i \rightarrow \tilde{t}_1 \tilde{t}_2^* +$
94 double diffraction	99 $\gamma^* q \rightarrow q$	77 $W_{L}^{\pm}W_{L}^{\pm} \rightarrow \tilde{W}_{L}^{\pm}\tilde{W}_{L}^{\pm}$	Technicolor:	$392 gg \to G^*$	$\begin{array}{c ccccccccccccccccccccccccccccccccccc$	$264 gg \rightarrow \tilde{t}_1 \tilde{t}_1^*$
95 low- p_{\perp} production	Photon-induced:	BSM Neutral Higgs:	149 $gg \rightarrow \eta_{tc}$	$393 q\overline{q} \rightarrow gG^*$	$\begin{array}{cccccccccccccccccccccccccccccccccccc$	$265 gg \rightarrow \tilde{t}_2 \tilde{t}_2^*$
Open heavy flavour:	$33 f_i \gamma \to f_i g$	151 $f_i \overline{f}_i \to H^0$	191 $f_i \bar{f}_i \rightarrow \rho_{t_i}^0$	$394 qg \rightarrow qG^*$	$\begin{array}{cccccccccccccccccccccccccccccccccccc$	$271 f_i f_j \to \tilde{q}_{iL} \tilde{q}_{jL}$
(also fourth generation)	$34 f_i \gamma \to f_i \gamma$	$152 gg \rightarrow H^0$	$\begin{array}{ccc} 101 & f_i \\ 192 & f_i \\ \hline f_i \rightarrow o^+ \end{array}$	$395 gg \to gG^*$	$\begin{array}{cccccccccccccccccccccccccccccccccccc$	$272 f_i f_j \to \tilde{q}_{iR} \tilde{q}_{jR}$
81 $f_i \overline{f}_i \to Q_k \overline{Q}_k$	54 $g\gamma \rightarrow f_k \overline{f}_k$	153 $\gamma \gamma \rightarrow \mathrm{H}^{0}$	$102 f_{1}f_{1} \rightarrow \omega^{0}$	Left–right symmetry:	$\begin{array}{cccccccccccccccccccccccccccccccccccc$	273 $f_i f_j \rightarrow \tilde{q}_{iL} \tilde{q}_{jR} +$
82 $gg \rightarrow Q_k \overline{Q}_k$	58 $\gamma\gamma \to f_k \overline{f}_k$	171 $f_i \overline{f}_i \rightarrow Z^0 H^0$	$\begin{array}{ccc} 100 & f_i f_i \rightarrow \omega_{tc} \\ 104 & f_i \overline{f}_i \rightarrow f_i \overline{f}_i \end{array}$	$341 \ell_i \ell_j \to \mathcal{H}_L^{\pm\pm}$	$\begin{bmatrix} 220 & I_i I_i \rightarrow \chi_1^- \chi_1^- \\ 227 & C \overline{C} & \tilde{c}^+ \tilde{c}^\pm \end{bmatrix}$	$274 f_i \overline{f}_j \to \tilde{q}_{iL} \tilde{q}_{jL}^*$
83 $q_i f_j \rightarrow Q_k f_l$	131 $f_i \gamma^*_T \to f_i g$	172 $f_i \overline{f}_i \to W^{\pm} H^0$	$105 f_1 \overline{f}_1 \longrightarrow f_2 \overline{f}_2$	$342 \ell_i \ell_j \to \mathrm{H}_R^{\pm\pm}$	$\begin{array}{cccc} 227 & \mathbf{f}_i \mathbf{f}_i \to \chi_2^- \chi_2^+ \\ 222 & \mathbf{f}_i \mathbf{f}_i \to \chi_2^- \chi_2^+ \end{array}$	275 $f_i \overline{f}_j \to \tilde{q}_i R \tilde{q}_j^* R$
84 $g\gamma \rightarrow Q_k \overline{Q}_k$	132 $f_i \gamma_L^* \to f_i g$	173 $f_i f_i \rightarrow f_i f_i H^0$	$\begin{array}{cccc} 155 & I_{i}I_{j} & I_{k}I_{l} \\ 361 & f_{\cdot}\overline{f}_{\cdot} \longrightarrow W^{+}W^{-} \end{array}$	343 $\ell_i^{\pm} \gamma \to \mathrm{H}_L^{\pm\pm} \mathrm{e}^{\mp}$	$\begin{array}{ccc} 228 & \mathbf{f}_i \mathbf{f}_i \to \chi_1^+ \chi_2^+ \\ & & & & \\ \end{array}$	276 $f_i \overline{f}_j \rightarrow \tilde{q}_{iL} \tilde{q}_{jR}^* +$
85 $\gamma \gamma \to \mathbf{F}_k \overline{\mathbf{F}}_k$	133 $f_i \gamma^*_T \to f_i \gamma$	174 $f_i f_i \rightarrow f_k f_l H^0$	$\begin{array}{cccc} 301 & \mathbf{I}_i \mathbf{I}_i \to \mathbf{W}_{\mathrm{L}} \mathbf{W}_{\mathrm{L}} \\ 262 & \mathbf{f}_i \mathbf{\overline{f}}_i \to \mathbf{W}^{\pm} \pi^{\mp} \end{array}$	$344 \ell_i^{\pm} \gamma \to \mathbf{H}_R^{\pm\pm} \mathbf{e}^{\mp}$	$229 f_i f_j \to \tilde{\chi}_1 \tilde{\chi}_1^{\pm}$	277 $f_i \overline{f}_i \rightarrow \tilde{q}_{jL} \tilde{q}_{jL}^*$
Closed heavy flavour:	$134 f_i \gamma_L^* \to f_i \gamma$	181 gg $\rightarrow Q_k \overline{Q}_k H^0$	$\begin{array}{cccc} 302 & 1_{i}1_{i} \rightarrow \mathbf{W}_{\mathrm{L}} \mathbf{\pi}_{\mathrm{tc}} \\ 262 & \mathbf{f}_{\cdot}\mathbf{f}_{\cdot} \rightarrow \pi^{+}\pi^{-} \end{array}$	345 $\ell_i^{\pm} \gamma \to \mathrm{H}_L^{\pm\pm} \mu^{\mp}$	$230 f_i f_j \to \chi_2 \chi_1^{\pm}$	278 $f_i \overline{f}_i \rightarrow \tilde{q}_{jR} \tilde{q}_{jR}^*$
86 $gg \rightarrow J/\psi g$	135 $g\gamma_T^* \to f_i \overline{f}_i$	182 $q_i \overline{q}_i \to Q_k \overline{Q}_k H^0$	$\begin{array}{ccc} 303 & \mathbf{I}_i \mathbf{I}_i \to \pi_{\mathrm{tc}} \pi_{\mathrm{tc}} \\ 264 & \mathbf{f}_i \mathbf{\overline{f}}_i \to \alpha \pi^0 \end{array}$	$346 \ell_i^{\pm} \gamma \to \mathbf{H}_R^{\pm\pm} \mu^{\mp}$	$\begin{array}{ccc} 231 & \mathbf{f}_i \mathbf{f}_j \to \tilde{\chi}_3 \tilde{\chi}_1^{\perp} \\ & & & \\ \end{array}$	279 gg $\rightarrow \tilde{q}_{iL}\tilde{q}_{iL}^*$
87 $gg \rightarrow \chi_{0c}g$	136 $g\gamma_L^* \to f_i \overline{f}_i$	183 $f_i \overline{f}_i \rightarrow g H^0$	$365 f \ f \ r \ r \ r'^0$	$347 \ell_i^{\pm} \gamma \to \mathbf{H}_L^{\pm\pm} \tau^{\mp}$	$232 f_i f_j \to \tilde{\chi}_4 \tilde{\chi}_1^{\pm}$	$280 \mathrm{gg} \to \tilde{\mathrm{q}}_{iR} \tilde{\mathrm{q}}_{iR}^* R$
88 $gg \rightarrow \chi_{1c}g$	137 $\gamma^*_{\mathbf{T}}\gamma^*_{\mathbf{T}} \to \mathbf{f}_i \overline{\mathbf{f}}_i$	184 $f_i g \rightarrow f_i H^0$	$\begin{array}{ccc} 303 & I_i I_i \rightarrow \gamma \pi & \text{tc} \\ 300 & f \overline{f} & 70 - 0 \end{array}$	$348 \ell_i^{\pm} \gamma \to \mathbf{H}_R^{\pm \pm} \tau^{\mp}$	$233 f_i \underline{f}_j \to \tilde{\chi}_1 \tilde{\chi}_2^{\pm}$	$281 \mathrm{bq}_i \to \tilde{\mathrm{b}}_1 \tilde{\mathrm{q}}_{iL}$
$89 \mathrm{gg} ightarrow \chi_{2\mathrm{c}}\mathrm{g}$	138 $\gamma^*_{\mathbf{T}}\gamma^*_{\mathbf{L}} \to \mathbf{f}_i \overline{\mathbf{f}}_i$	185 $gg \rightarrow gH^0$	$\begin{array}{cccccccccccccccccccccccccccccccccccc$	$349 f_i \underline{f}_i \to \mathbf{H}_L^{++} \mathbf{H}_L^{}$	$234 f_i f_j \to \tilde{\chi}_2 \tilde{\chi}_2^\perp$	$282 \mathrm{bq}_i \to \tilde{\mathrm{b}}_2 \tilde{\mathrm{q}}_{iR}$
$104 \mathrm{gg} \to \chi_{0\mathrm{c}}$	139 $\gamma_{\rm L}^* \gamma_{\rm T}^* \to {\rm f}_i \overline{\rm f}_i$	156 $f_i \overline{f}_i \to A^0$	$307 I_i I_i \rightarrow Z \pi_{tc}$	$350 f_i f_i \to H_R^{++} H_R^{}$	$235 f_i \underline{f}_j \to \tilde{\chi}_3 \tilde{\chi}_2^{\pm}$	283 $bq_i \rightarrow \tilde{b}_1 \tilde{q}_{iR} +$
$105 \mathrm{gg} \to \chi_{2\mathrm{c}}$	140 $\gamma_{\rm L}^* \gamma_{\rm L}^* \to {\rm f}_i \overline{{\rm f}}_i$	$157 gg \rightarrow A^0$	$\begin{array}{ccc} 368 & \mathrm{I}_i \mathrm{I}_i \to \mathrm{W}^+ \pi_{\mathrm{tc}}^+ \\ 370 & \mathrm{f} \overline{\mathrm{f}} & \mathrm{W}^+ \mathrm{70} \end{array}$	$351 f_i f_j \to f_k f_l H_{L_j}^{\pm\pm}$	$236 f_i f_j \to \tilde{\chi}_4 \tilde{\chi}_2^{\pm}$	284 $b\overline{q}_i \rightarrow \tilde{b}_1 \tilde{q}_i^* L$
$106 gg \to J/\psi\gamma$	80 $q_i \gamma \to q_k \pi^{\pm}$	158 $\gamma \gamma \rightarrow A^0$	$\begin{array}{ccc} 370 & I_i I_j \rightarrow W_{\overline{L}} Z_{\overline{L}} \\ 371 & C \overline{C} & W^{\pm} \end{array}$	$352 f_i f_j \to f_k f_l H_R^{\pm \pm}$	$237 f_i \underline{f}_i \to \tilde{g} \tilde{\chi}_1$	285 $b\overline{q}_i \rightarrow \tilde{b}_2 \tilde{q}_{iR}^*$
$107 g\gamma \rightarrow J/\psi g$	Light SM Higgs:	$176 f_i \overline{f}_i \to Z^0 A^0$	371 $I_i I_j \rightarrow W_L^{\pm} \pi_{tc}^{\pm}$	$353 f_i f_i \to Z_R^0$	238 $f_i \underline{f}_i \to \tilde{g} \tilde{\chi}_2$	$286 \mathbf{b} \overline{\mathbf{q}}_i \to \tilde{\mathbf{b}}_1 \tilde{\mathbf{q}}_i^* \mathbf{B} +$
$108 \gamma\gamma \to J/\psi\gamma$	$3 f_i \overline{f}_i \to h^0$	$177 f_i \overline{f}_j \to W^{\pm} A^0$	$\begin{array}{ccc} 372 & \mathbf{I}_i \mathbf{I}_j \to \pi_{\mathrm{tc}}^+ \mathbf{Z}_{\mathrm{L}}^* \\ \mathbf{z}_{\mathrm{T}}^{-2} & \mathbf{z}_{\mathrm{T}}^{-2} & \pm 0 \end{array}$	$354 f_i f_j \to W_R^{\pm}$	$239 f_i \underline{f}_i \to \tilde{g} \tilde{\chi}_3$	$287 f_i \overline{f}_i \to \tilde{b}_1 \tilde{b}_1^*$
W/Z production:	$24 \mathbf{f}_i \mathbf{\overline{f}}_i \to \mathbf{Z}^0 \mathbf{h}^0$	178 $f_i f_j \rightarrow f_i f_j A^0$	$\begin{array}{ccc} 373 & \mathbf{f}_i \mathbf{f}_j \to \pi_{\mathrm{tc}}^\pm \pi_{\mathrm{tc}}^\bullet \\ \mathbf{a} \overline{\mathbf{f}}_i & \mathbf{f}_i \overline{\mathbf{f}}_j \to \pi_{\mathrm{tc}}^\pm \pi_{\mathrm{tc}}^\bullet \end{array}$	SUSY:	$240 f_i f_i \to \tilde{g} \tilde{\chi}_4$	$288 f_i \overline{f}_i \to \tilde{b}_2 \tilde{b}_2^*$
$1 f_i \underline{f}_i \to \gamma^* / \mathbf{Z}^0$	26 $f_i \overline{f}_j \rightarrow W^{\pm} h^0$	179 $f_i f_j \rightarrow f_k f_l A^0$	$374 f_i f_j \to \gamma \pi_{tc}^+$	$201 f_i \overline{f}_i \to \tilde{e}_L \tilde{e}_L^*$	$241 f_i \overline{f}_j \to \tilde{g} \tilde{\chi}_1^{\pm}$	$289 \text{gg} \rightarrow \tilde{b}_1 \tilde{b}_1^*$
$2 f_i f_j \to W^{\pm}$	$32 f_i g \rightarrow f_i h^0$	186 $gg \to Q_k \overline{Q}_k A^0$	$375 f_i f_j \rightarrow Z^0 \pi_{tc}^{\pm}$	$202 f_i \overline{f}_i \to \tilde{e}_R \tilde{e}_R^*$	$242 f_i \overline{f}_j \to \tilde{g} \tilde{\chi}_2^{\pm}$	$\begin{array}{ccc} 290 & gg \rightarrow \tilde{b}_2 \tilde{b}_2^* \end{array}$
$22 f_i f_i \to Z^0 Z^0$	$102 gg \rightarrow h^0$	187 $q_i \overline{q}_i \rightarrow Q_k \overline{Q}_k A^0$	$376 f_i f_j \rightarrow W^{\perp} \pi^0_{tc}$	$203 f_i \overline{f}_i \to \tilde{e}_L \tilde{e}_R^* +$	$243 f_i \overline{f}_i \to \tilde{g}\tilde{g}$	$\begin{array}{ccc} 291 & bb \rightarrow \tilde{b}_1 \tilde{b}_1 \end{array}$
$23 f_i \overline{f}_j \to Z^0 W^{\pm}$	$103 \gamma\gamma \to h^0$	188 $f_i \overline{f}_i \rightarrow g A^0$	$377 f_i f_j \to W^{\pm} \pi'^{\circ}_{tc}$	$204 f_i \overline{f}_i \to \tilde{\mu}_L \tilde{\mu}_L^*$	$244 gg \rightarrow \tilde{g}\tilde{g}$	$\begin{array}{ccc} 201 & 50 & 5151 \\ 292 & bb \rightarrow \tilde{b}_{2}\tilde{b}_{2} \end{array}$
$25 f_i \overline{f}_i \to W^+ W^-$	$110 f_i \overline{f}_i \to \gamma h^0$	189 $f_i g \rightarrow f_i A^0$	$381 \mathbf{q}_i \mathbf{q}_j \to \mathbf{q}_i \mathbf{q}_j$	$205 f_i \overline{f}_i \to \tilde{\mu}_R \tilde{\mu}_R^*$	$246 f_i g \to \tilde{q}_{iL} \tilde{\chi}_1$	$292 bb \rightarrow b_2 b_2$ $203 bb \rightarrow \tilde{b}_2 \tilde{b}_2$
$15 f_i \overline{f}_i \to g Z^0$	111 $f_i \overline{f}_i \rightarrow gh^0$	$190 gg \rightarrow gA^0$	$382 \mathbf{q}_i \overline{\mathbf{q}}_i \to \mathbf{q}_k \overline{\mathbf{q}}_k$	$206 f_i \overline{f}_i \to \tilde{\mu}_L \tilde{\mu}_R^* +$	$247 f_i g \to \tilde{q}_{iR} \tilde{\chi}_1$	$293 bb \rightarrow b_1 b_2$ $204 br \rightarrow \tilde{b}_1 \tilde{r}$
$16 f_i \overline{f}_j \to g W^{\pm}$	112 $f_i g \rightarrow f_i h^0$	Charged Higgs:	$\begin{array}{ccc} 383 & \mathbf{q}_i \overline{\mathbf{q}}_i \to \mathbf{g} \mathbf{g} \\ \end{array}$	$207 f_i \overline{f}_i \longrightarrow \tilde{\tau}_1 \tilde{\tau}_1^*$	$248 f_i g \to \tilde{q}_{iL} \tilde{\chi}_2$	254 $\text{bg} \rightarrow \text{big}$
$30 f_i g \to f_i Z^0$	$113 gg \to gh^0$	143 $f_i \overline{f}_j \to H^+$	$384 I_i g \rightarrow I_i g$	$208 f_i \overline{f}_i \to \tilde{\tau}_2 \tilde{\tau}_2^*$	$249 f_i g \to \tilde{q}_{iR} \tilde{\chi}_2$	$ \begin{array}{c} 295 & \overline{\text{bg}} \rightarrow \overline{\text{b2g}} \\ 206 & \overline{\text{bb}} \rightarrow \tilde{\text{b}} \tilde{\text{b}}^{*} \end{array} $
$31 f_i g \to f_k W^{\pm}$	$121 \mathrm{gg} \to \mathrm{Q}_k \overline{\mathrm{Q}}_k \mathrm{h}^0$	$161 f_i g \rightarrow f_k H^+$	$380 gg \rightarrow q_k q_k$	$209 f_i \overline{f}_i \to \tilde{\tau}_1 \tilde{\tau}_2^* +$		$290 DD \rightarrow D_1D_2 +$
$19 f_i \overline{f}_i \to \gamma Z^0$	122 $q_i \overline{q}_i \rightarrow Q_k \overline{Q}_k h^0$	$401 gg \to \overline{t}bH^+$	$\begin{array}{ccc} 380 & gg \rightarrow gg \\ 387 & f \overline{f} & O \end{array}$			
$20 f_i \overline{f}_j \to \gamma W^{\pm}$	$123 f_i f_j \to f_i f_j h^0$	$402 q\overline{q} \to \overline{t}bH^+$	$\begin{array}{ccc} 387 & \mathbf{I}_i \mathbf{I}_i \to \mathbf{Q}_k \mathbf{Q}_k \\ 388 & \mathbf{Q}_k \end{array}$			
$35 f_i \gamma \rightarrow f_i Z^0$	124 $f_i f_i \rightarrow f_i f_i h^0$	· · · · · · · · · · · · · · · · · · ·	$388 gg \rightarrow Q_k Q_k$			

Couse on Physics at the LHC

From Partons to Jets

From partons to color neutral hadrons:

Fragmentation:

Parton splitting into other partons [QCD: re-summation of leading-logs] ["Parton shower"]

Hadronization:

Parton shower forms hadrons [non-perturbative, only models]

Decay of unstable hadrons [perturbative QCD, electroweak theory]



Hadronization & Decays

Detector simulation

GEANT Geometry And Tracking

Detailed description of detector geometry [sensitive & insensitive volumes]

Tracking of all particles through detector material ...

➤ Detector response



Developed at CERN since 1974 (FORTRAN) [Today: Geant4; programmed in C⁺⁺]

Luminosity and cross-section measurements



Cross section & Luminosity



Background

measured from data or calculated from theory

$$\sigma = \frac{N^{\text{obs}} - N^{\text{bkg}}}{\int \mathcal{L} \, \mathrm{d}t \cdot \varepsilon}$$

Luminosity

determined by accelerator, triggers, ...

Efficiency

many factors, optimized by experimentalist

Cross section & Luminosity



$$\Phi_a = \frac{N_a}{A} = n_a v_a$$

 Φ_a : flux

- na: density of particle beam
- v_a : velocity of beam particles

$$\dot{N} = \Phi_a \cdot N_b \cdot \sigma_b$$

- N : reaction rate
- N_b : target particles within beam area σ_a : effective area of single
- scattering center

$$L = \Phi_a \cdot N_b$$

L : luminosity

$$\dot{N} \equiv L \cdot \sigma$$
$$N = \sigma \cdot \int L \, dt \qquad \sigma = N/L$$

integrated luminosity

Collider experiment:

standard deviation of beam profile in y \mathbf{O}_{V} :

Van-der-Meer separation scan



Minimum bias events



Characteristics of inelastic p-p collisions

Particle density in minimum bias events

Soft QCD (PT threshold on tracks: 50 MeV)



Charged particle p_⊤ spectrum



Couse on Physics at the LHC

Jet physics



Jet production @ LHC







Calorimeter Jet

[extracted from calorimeter clusters]

Understanding of detector response Knowledge about dead material Correct signal calibration Potentially include tracks

Hadron Jet

[might include electrons, muons ...]

Hadronization Fragmentation Parton shower Particle decays

Parton Jet [quarks and gluons]

Proton-proton interactions Initial and final state radiation Underlying event

From particle energy to

"Measurement"

Compensate hadronization; energy in/outside jet cone

original parton energy

Needs Calibration

Jet

"Theory"

to particle energy

Compensate energy loss

due to neutrinos, nuclear

excitation ...

From measured energy

Jet reconstruction

Iterative cone algorithms:

Jet defined as energy flow within a cone of radius R in (y, ϕ) or (η, ϕ) space:

 $R = \sqrt{(y - y_0)^2 + (\phi - \phi_0)^2}$

Sequential recombination algorithms:

Define distance measure d_{ij} ... Calculate d_{ij} for all pairs of objects ... Combine particles with minimum d_{ij} below cut ... Stop if minimum d_{ij} above cut ...

e.g. k⊤-algorithm: [see later]

$$d_{\rm ij} = \min\left(k_{\rm T,i}^2, k_{\rm T,j}^2\right) \frac{\Delta R {\rm ij}}{R}$$





Couse on Physics at the LHC



['bin-by-bin' unfolding]

 $N_{\rm part} = N_{\rm meas}$

part

meas

Resolution unfolding

Measured spectrum = Real spectrum \otimes Experim. resolution



Inclusive jet cross-section

Cross section is huge (~ Tevatron x 100)

Very good agreement with NLO QCD over nine orders of magnitude

PT extending from 20 to 500 GeV

Main uncertainty: Jet Energy Scale (3-4%)



Inclusive jet cross sections: 3-jet / 2-jet ratio

hep-ex 1106.0647, PLB 702 (2011) 336



Jets: angular correlations

Difference in azimuth of the two leading jets Probe of QCD high-order processes Very slight dependence on JES No dependence on luminosity





Dijet mass

Search for numerous resonances BSM:

string resonance, excited quarks, axi-gluons, colorons, E6 diquarks, W' and Z', RS gravitons

Four-parameter fit to describe QCD shape:

$$\frac{d\sigma}{dm} = p_0 \frac{\left(1 - \frac{m}{\sqrt{s}}\right)^{p_1}}{\left(\frac{m}{\sqrt{s}}\right)^{B}};$$
$$B = p_2 + p_3 \left(\frac{m}{\sqrt{s}}\right)$$



End of Lecture 2

W and Z bosons



Couse on Physics at the LHC

Vector boson production





- At LHC energies these processes take place at low values of Bjorken-x
- Only sea quarks and gluons are involved
- At EW scales sea is driven by the gluon, i.e. x-sections dominated by gluon uncertainty
- ► Constraints on sea and gluon distributions

W and Z boson decays



Leptonic decays (e/µ): very clean, but small(ish) branching fractions Hadronic decays: two-jet final states; large QCD dijet background Tau decays: somewhere in between...

W and Z boson signatures

[CERN-OPEN-2008-020]



Additional hadronic activity → recoil, not as clean as e⁺e⁻ Precision measurements: only leptonic decays

Couse on Physics at the LHC

Starting point for many hadron collider analyses: isolated high-p_T leptons → discriminate against QCD jets ...

QCD jets can be mis-reconstructed as leptons ("fake leptons")

QCD jets may contain real leptons e.g. from semileptonic B decays $[B \rightarrow IvX]$

→ soft and surrounded by other particles

"Tight" lepton selection ...

Require e/μ with $p_T > (at least) 20 \text{ GeV}$ Track isolation, e.g. $\sum p_T$ of other tracks in cone of $\Delta R=0.1$ less than 10% of lepton p_T

Calorimeter isolation, e.g. energy deposition from other particles in cone of ΔR =0.2 less than 10%



Dilepton mass spectrum at 7 TeV



Example: CMS W Analysis

Select isolated electrons and muons ... [muons: $p_T > 9$ GeV; electrons: $p_T > 20$ GeV]

Investigate transverse mass ... [Use $E_{T,miss}$; $M_T = (p_{lep} + E_{T,miss})^{\frac{1}{2}}$]



The W signal yield is extracted from a binned likelihood fit to the M_T distribution. Three different contributions:

- W signal
- QCD background
- other (EWK) backgrounds.

W/Z production at 7 TeV



W, Z cross-section v.s. \sqrt{s}

hep-ex 1012.2466, JHEP 01 (2011) 080



W+/W- charge asymmetry

NNLO cross sections: scale uncertainties very small

W rapidity: asymmetry [sensitivity to PDFs]

$$A_W(y) = \frac{\mathrm{d}\sigma(W^+)/\mathrm{d}y - \mathrm{d}\sigma(W^-)/\mathrm{d}y}{\mathrm{d}\sigma(W^+)/\mathrm{d}y + \mathrm{d}\sigma(W^-)/\mathrm{d}y}$$

Proton-Proton Collider:

symmetry around y=0 ...

PDFs:

```
u(x) > d(x) for large x ...
more W<sup>+</sup> at positive rapidity
d/u ratio < 1 ...
always more W<sup>+</sup> than W<sup>-</sup>
```



W + Jets multiplicity

$|\eta| < 2.8$ and $p_{\rm T} > 20$ GeV

arXiv:1012.5382



W + Jets P_T

Tails are important in several Exotica and SUSY searches



SM processes measured at LHC





JHEP10(2011)132 PLB701(2011)535 CMS-PAS-EWK-10-012Couse on Physics at the LHC CMS-PAS-EWK-11-010

W Mass Determination

Template method:

Fit templates (from MC simulation) with different m_W to data

→ W mass from best fit

Requires very good modeling of physics & detector

Templates for $m_W = 80.4 \pm 1.6 \text{ GeV}$



Ultimate LHC goal: m_W uncertainty of 15 MeV [via combination]