

# Course on Physics at the LHC

## Lecture 2

# Introduction to collisions at LHC

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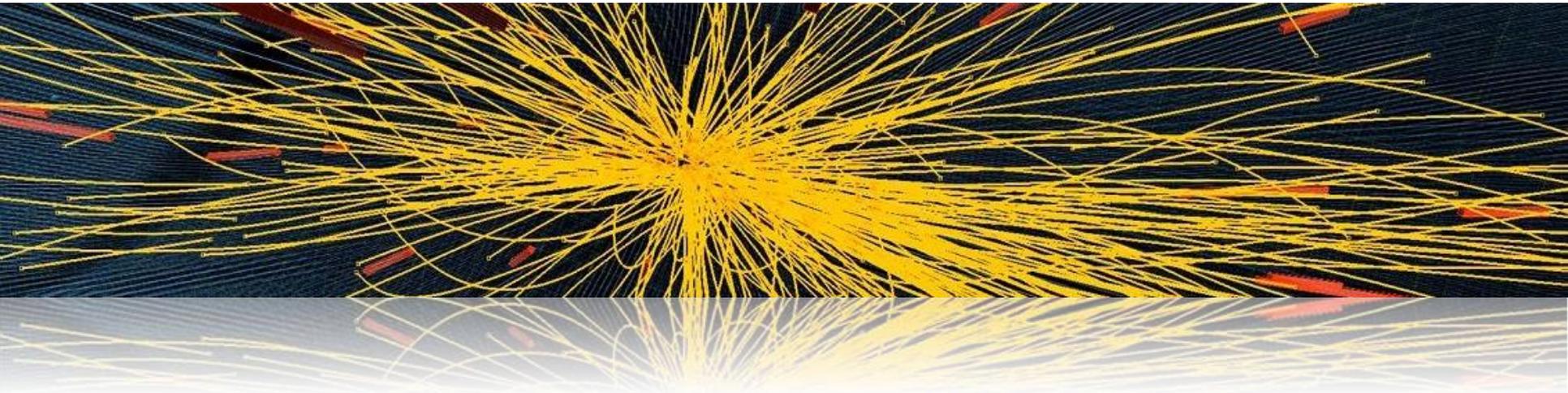


LABORATÓRIO DE INSTRUMENTAÇÃO  
E FÍSICA EXPERIMENTAL DE PARTÍCULAS  
*partículas e tecnologia*

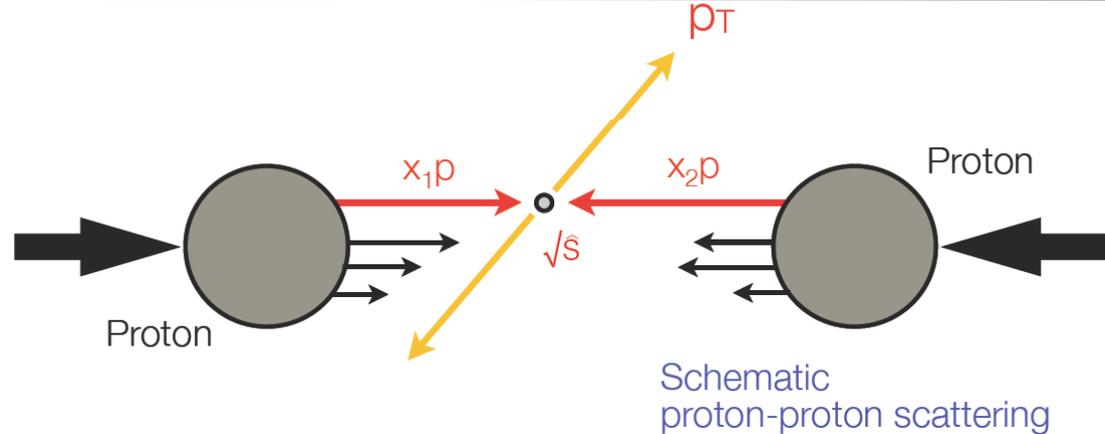
# Introduction to collisions at LHC

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

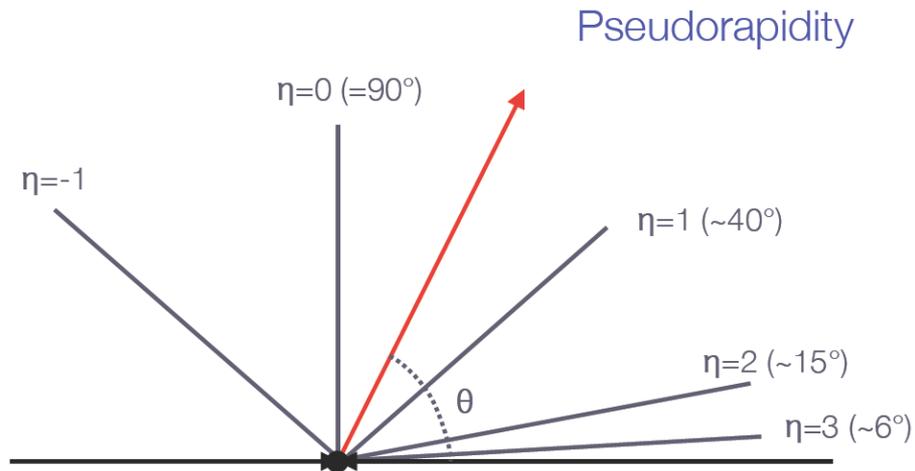


# Kinematical variables

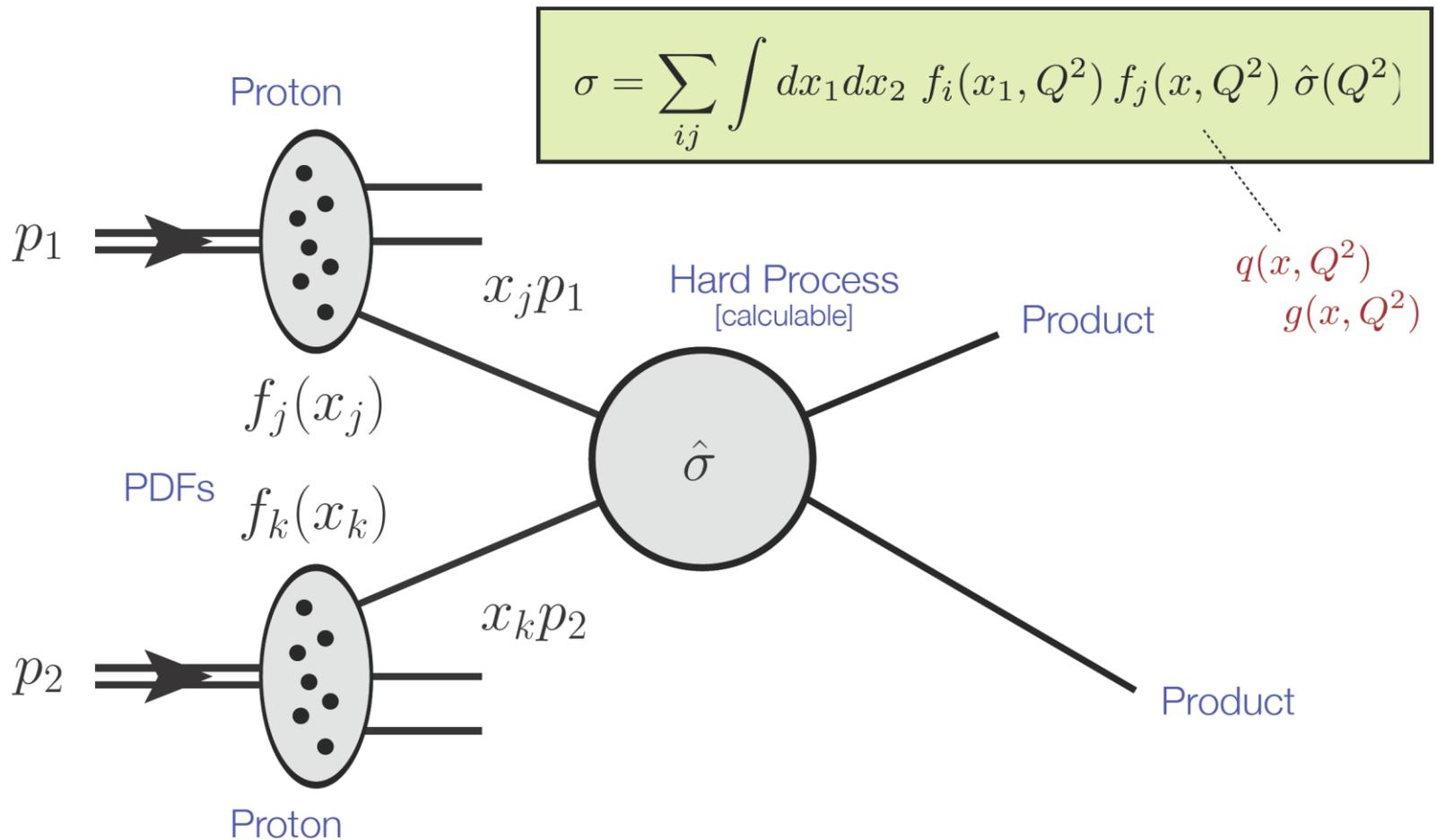


Relevant kinematic variables:

- Transverse momentum:  $p_T$
- Rapidity:  $y = \frac{1}{2} \cdot \ln \frac{E-p_z}{E+p_z}$
- Pseudorapidity:  $\eta = -\ln \tan \frac{1}{2}\theta$
- Azimuthal angle:  $\varphi$

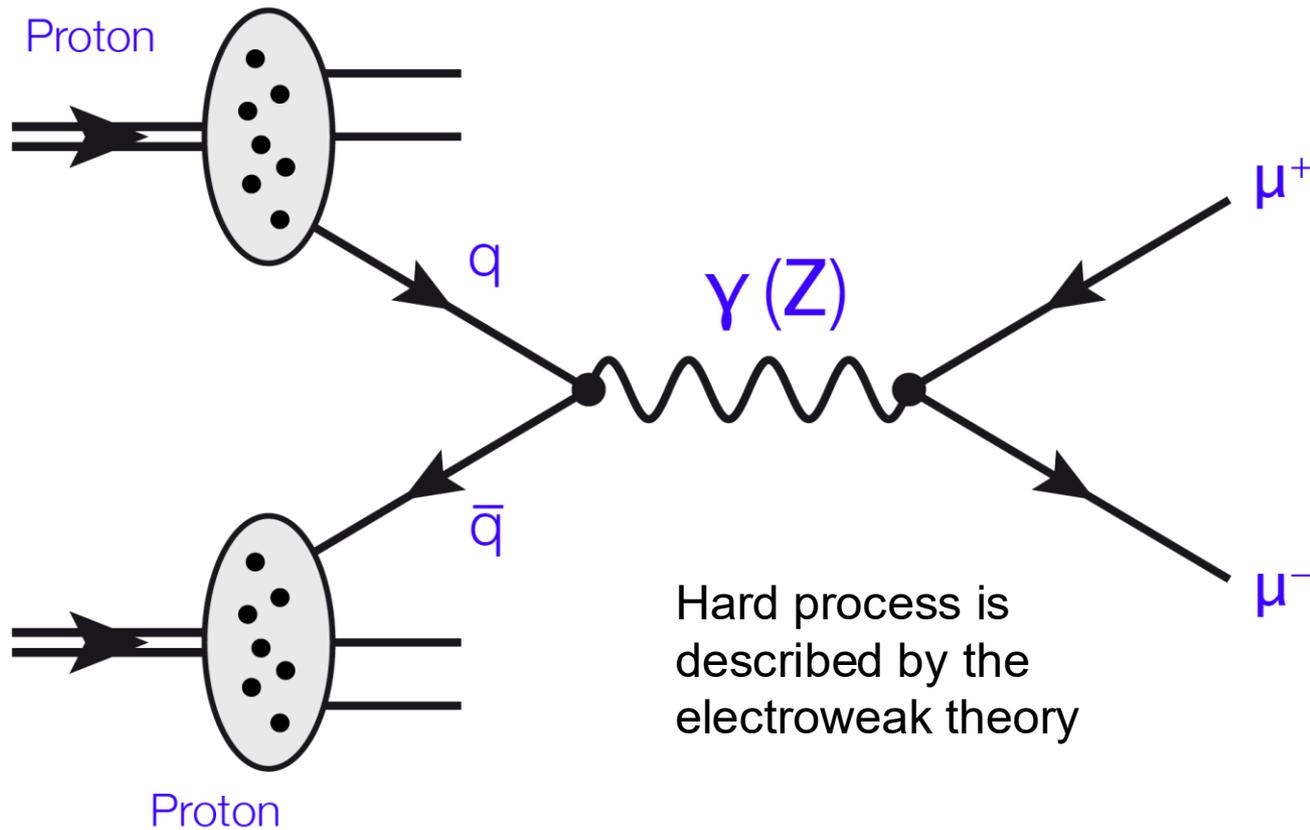


# Proton-Proton Scattering

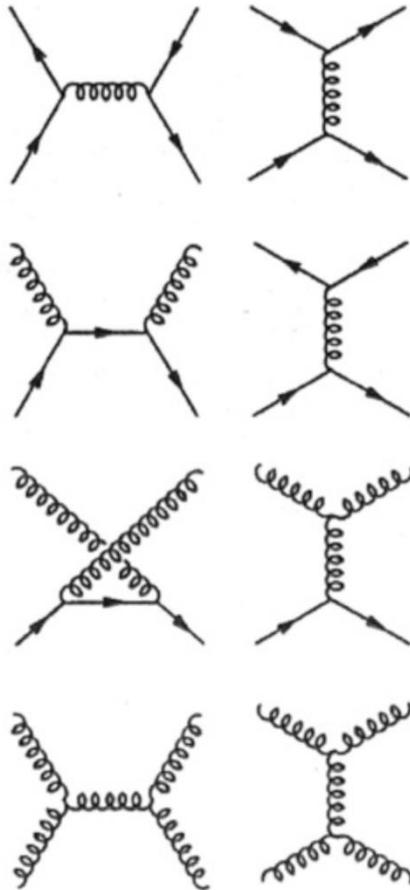


# Example: Drell-Yan Process

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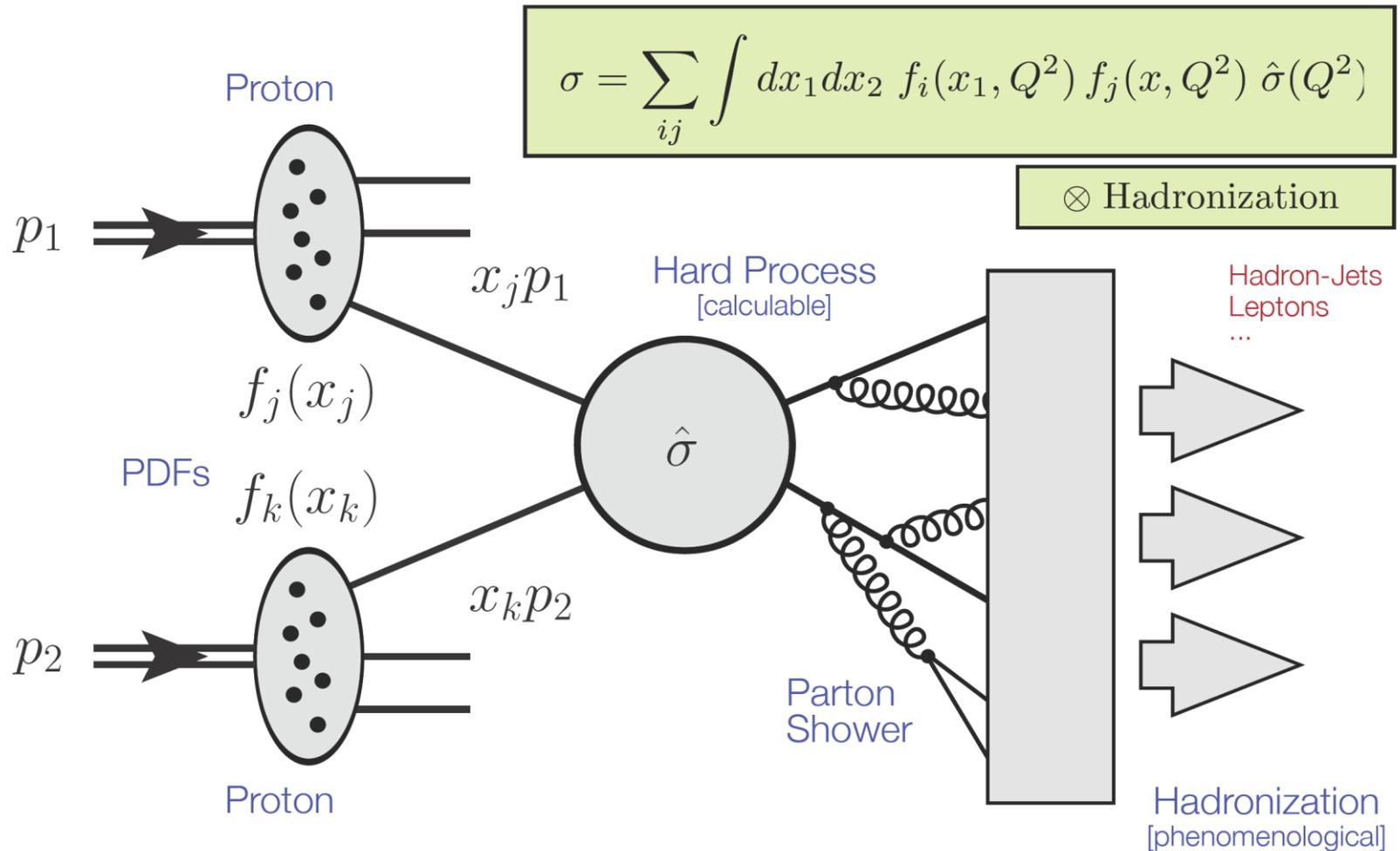


# QCD processes



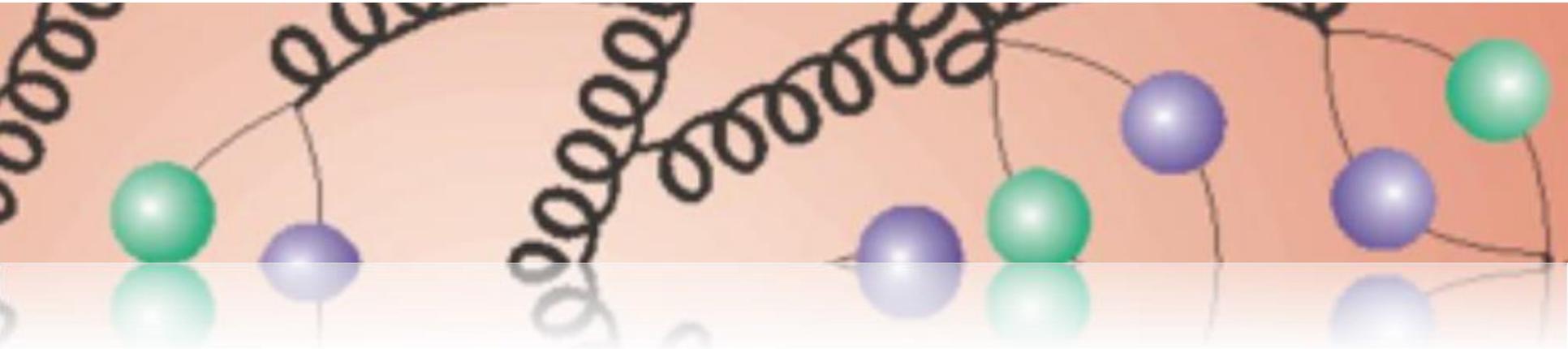
| Subprocess  | $ \mathcal{M} ^2/g_s^4$  | $ \mathcal{M}(90^\circ) ^2/g_s^4$ |
|---|--|-----------------------------------|
| $\left. \begin{array}{l} qq' \rightarrow qq' \\ q\bar{q}' \rightarrow q\bar{q}' \end{array} \right\}$ | $\frac{4}{9} \frac{\hat{s}^2 + \hat{u}^2}{\hat{t}^2}$  | 2.2                               |
| $qq \rightarrow qq$   | $\frac{4}{9} \left( \frac{\hat{s}^2 + \hat{u}^2}{\hat{t}^2} + \frac{\hat{s}^2 + \hat{t}^2}{\hat{u}^2} \right) - \frac{8}{27} \frac{\hat{s}^2}{\hat{u}\hat{t}}$ | 3.3                               |
| $q\bar{q} \rightarrow q'\bar{q}'$   | $\frac{4}{9} \frac{\hat{t}^2 + \hat{u}^2}{\hat{s}^2}$  | 0.2                               |
| $q\bar{q} \rightarrow q\bar{q}$   | $\frac{4}{9} \left( \frac{\hat{s}^2 + \hat{u}^2}{\hat{t}^2} + \frac{\hat{t}^2 + \hat{u}^2}{\hat{s}^2} \right) - \frac{8}{27} \frac{\hat{u}^2}{\hat{s}\hat{t}}$ | 2.6                               |
| $q\bar{q} \rightarrow gg$   | $\frac{32}{27} \frac{\hat{u}^2 + \hat{t}^2}{\hat{u}\hat{t}} - \frac{8}{3} \frac{\hat{u}^2 + \hat{t}^2}{\hat{s}^2}$   | 1.0                               |
| $gg \rightarrow q\bar{q}$   | $\frac{1}{6} \frac{\hat{u}^2 + \hat{t}^2}{\hat{u}\hat{t}} - \frac{3}{8} \frac{\hat{u}^2 + \hat{t}^2}{\hat{s}^2}$   | 0.1                               |
| $qg \rightarrow qg$   | $\frac{\hat{s}^2 + \hat{u}^2}{\hat{t}^2} - \frac{4}{9} \frac{\hat{s}^2 + \hat{u}^2}{\hat{u}\hat{s}}$   | 6.1                               |
| $gg \rightarrow gg$   | $\frac{9}{4} \left( \frac{\hat{s}^2 + \hat{u}^2}{\hat{t}^2} + \frac{\hat{s}^2 + \hat{t}^2}{\hat{u}^2} + \frac{\hat{u}^2 + \hat{t}^2}{\hat{s}^2} + 3 \right)$   | 30.4                              |

# Proton-Proton Scattering: final state



$$\sigma = \sum_{ij} \int dx_1 dx_2 f_i(x_1, Q^2) f_j(x_2, Q^2) \hat{\sigma}(Q^2)$$

# QCD & parton densities



# Lepton-proton scattering and proton structure



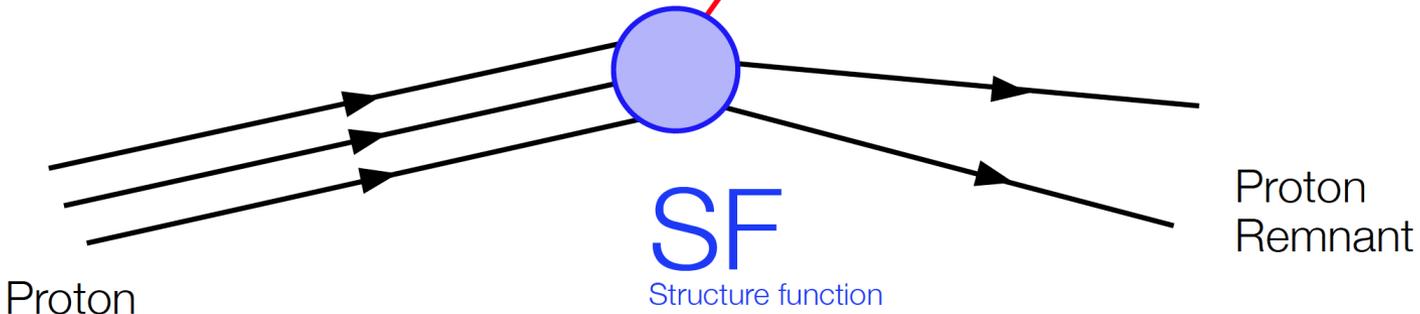
Cross Section:

$$d\sigma \sim \underbrace{d\sigma_{eq}}_{4\pi\alpha^2/q^4} \times \underbrace{F_2}_{x \cdot \sum e_q^2 q(x)}$$

$$Q^2 = -q^2 = -(k-k')^2$$

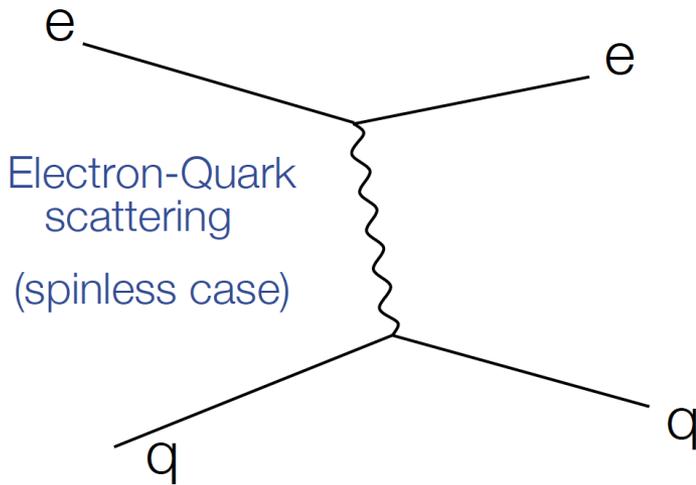
$$\alpha = \frac{1}{4\pi\epsilon_0} \frac{e^2}{\hbar c} \approx \frac{1}{137}$$

$\alpha$  = Fine-structure constant  
 $\epsilon_0$  = electric constant  
 $e$  = elementary charge  
 $\hbar$  = reduced Planck constant  
 $c$  = speed of light in a vacuum



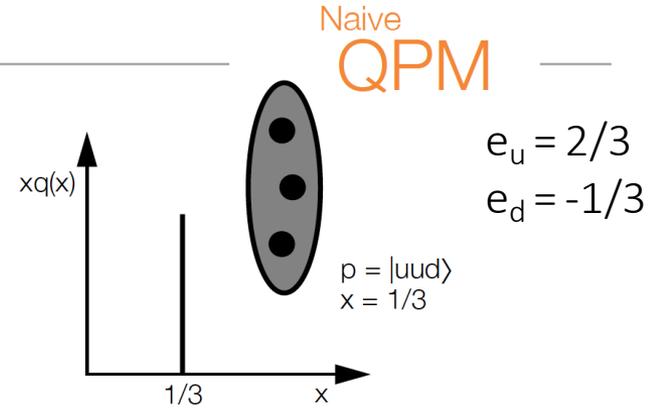
**SF**  
 Structure function  
 describes proton structure  
 probability to find quark with mom. fraction  $x$

# Structure Function



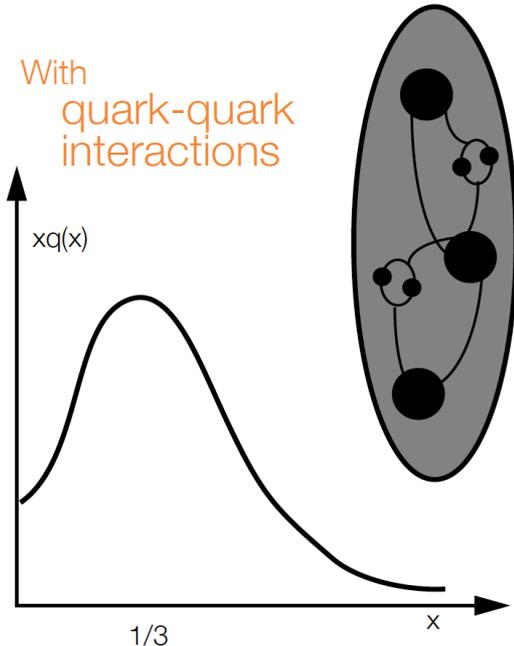
$$\frac{d\sigma(eq)}{dq^2} = \frac{4\pi\alpha^2}{q^4} e_q^2$$

Rutherford scattering on pointlike target



$$\frac{d\sigma(ep)}{dq^2} = \frac{4\pi\alpha^2}{q^4} [2e_u^2 + e_d^2] = \frac{4\pi\alpha^2}{q^4}$$

With quark-quark interactions

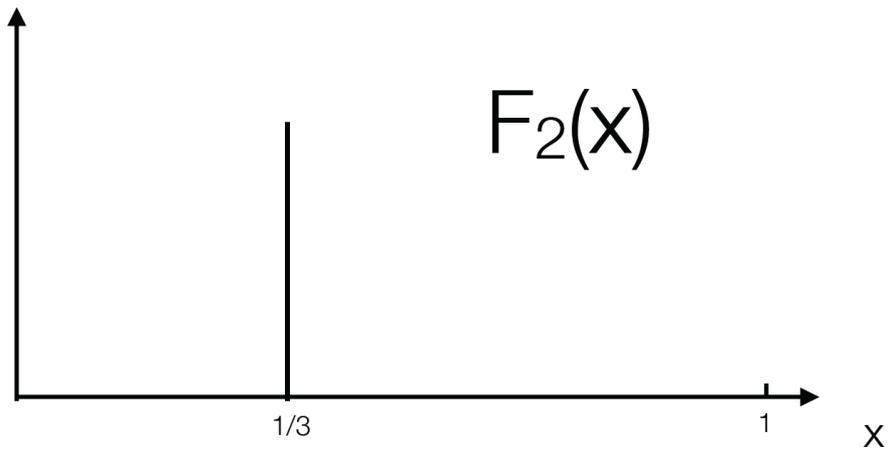


$$\frac{d\sigma(ep)}{dx dq^2} = \frac{4\pi\alpha^2}{q^4} [e_u^2 u(x) + e_d^2 d(x) + \dots]$$

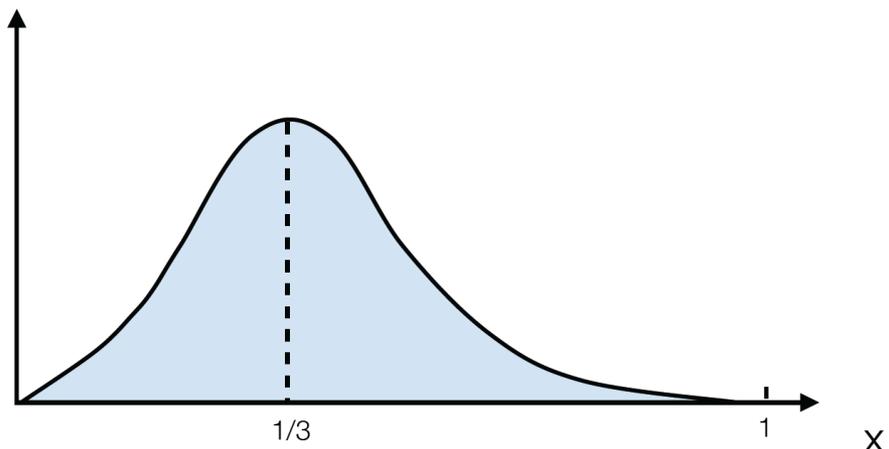
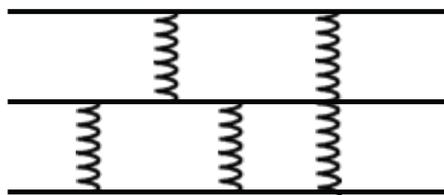
$$= \frac{4\pi\alpha^2}{q^4} \frac{F_2(x)}{x}$$

QPM: Structure Functions  $F_2$  independent of  $Q^2$

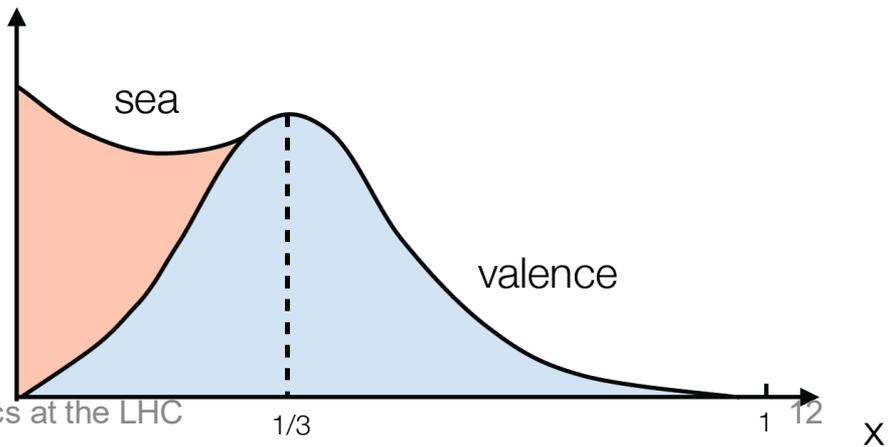
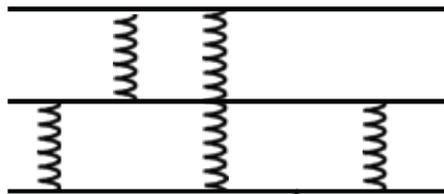
Proton Three valence quarks



Proton Three bound valence quarks



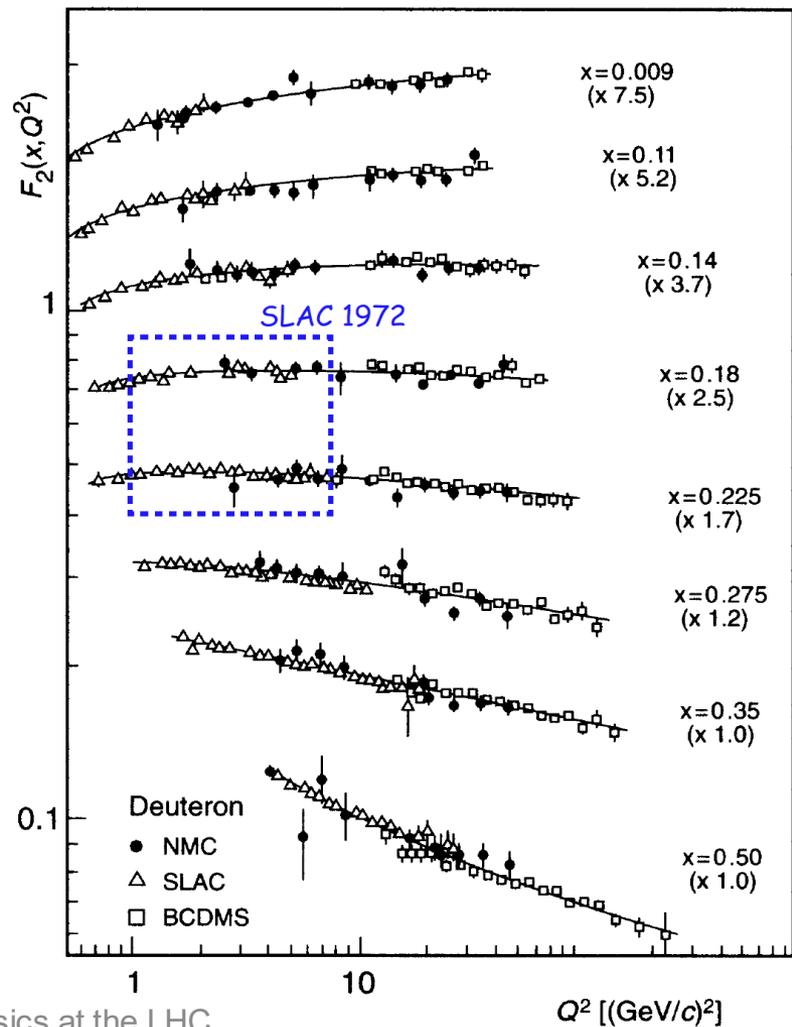
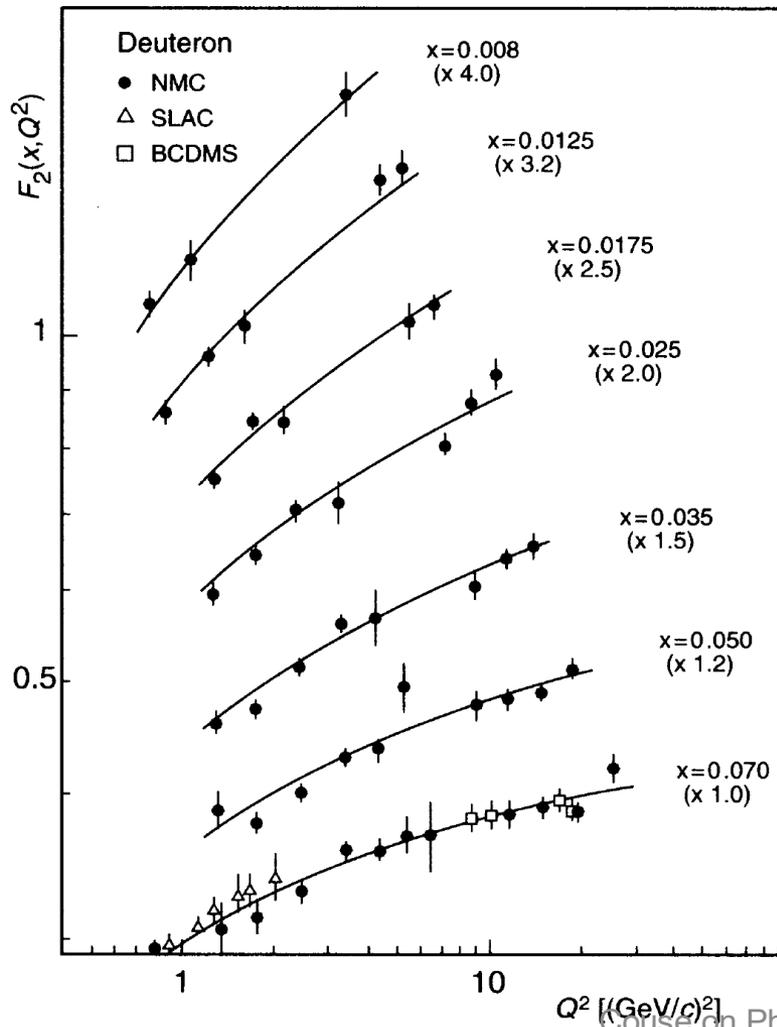
Proton Bound valence quarks + gluon radiation



[see e.g. Halzen/Martin]

# Scaling violation

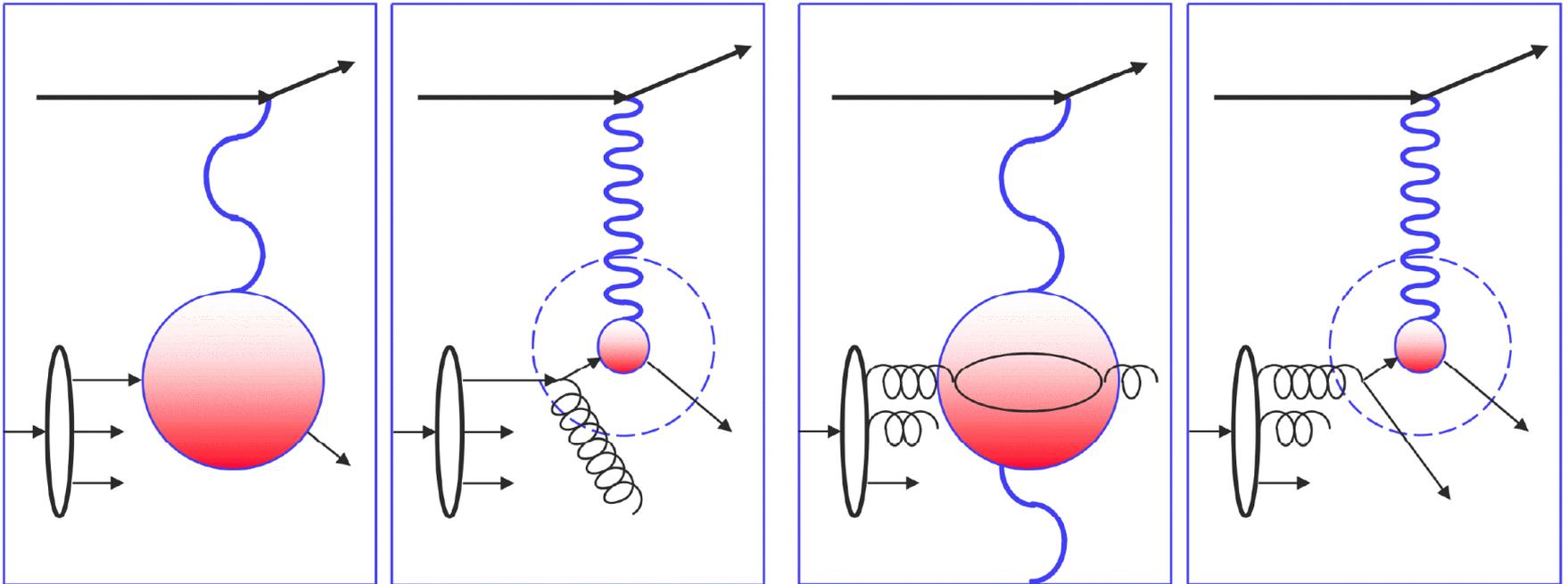
$$F_2(x, Q^2) = \sum e_q^2 x q(x, Q^2)$$



# Scaling violation

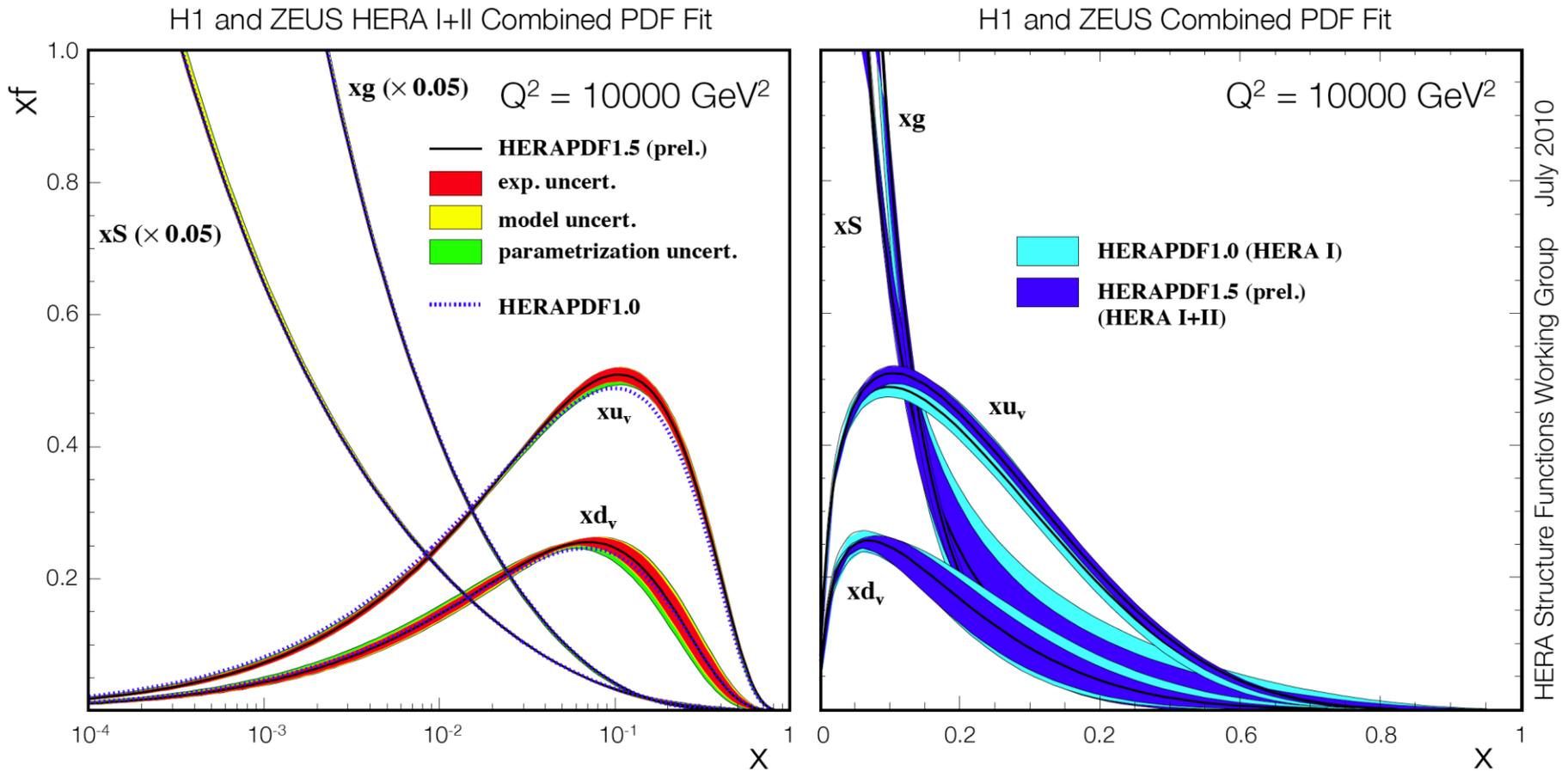
Proton quark dominated:  
 $Q^2 \uparrow \Rightarrow F_2 \downarrow$  for fixed  $x$

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

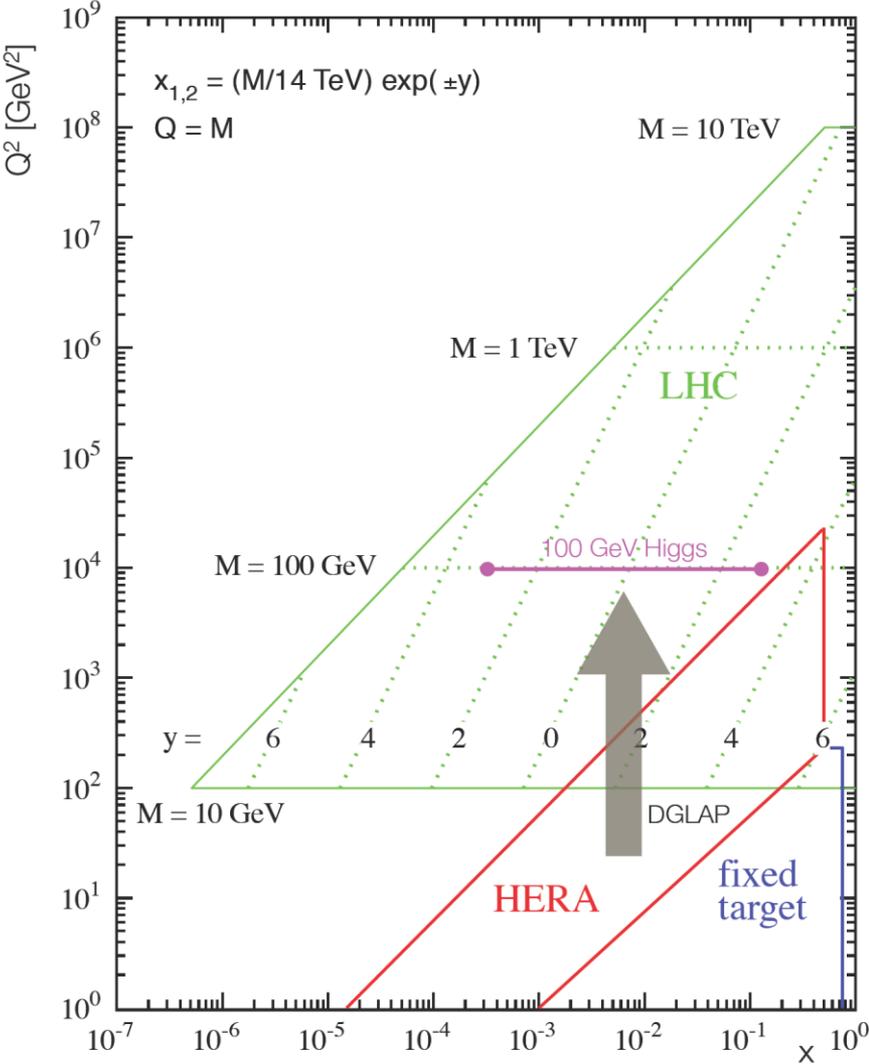
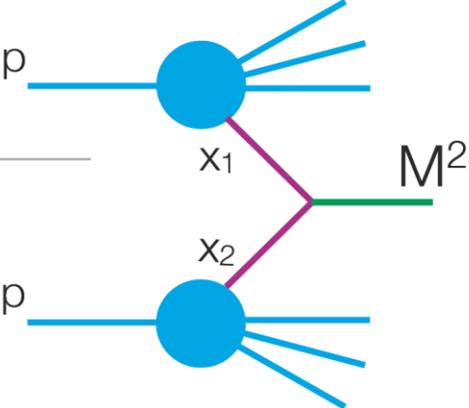


$Q^2$ -evolution described by DGLAP Equations

# Proton parton densities



# Particle production @ LHC



LHC parton kinematics

$pp \rightarrow X_M + \text{remnants}$

$X_M$ : particle with mass  $M$   
e.g. Higgs

$$M^2 = x_1 x_2 \cdot s$$

i.e. to produce a particle with mass  $M$  at LHC energies ( $\sqrt{s} = 14 \text{ TeV}$ )

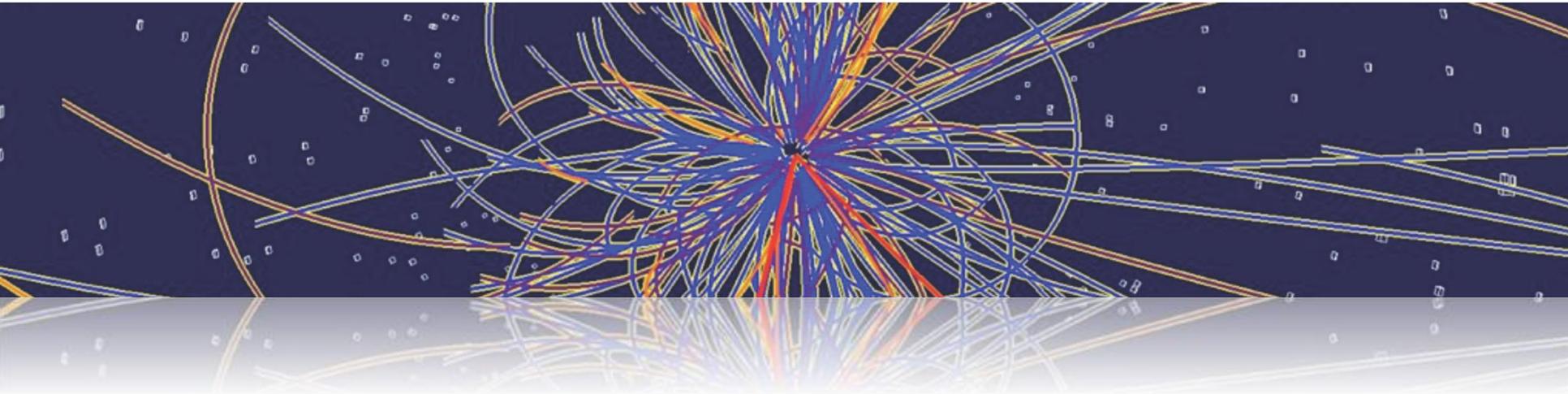
$$\langle x \rangle = \sqrt{x_1 x_2} = M/\sqrt{s}$$

$[x_1 = x_2: \text{mid-rapidity}]$

LHC needs:

- Knowledge of parton densities
- Extrapolation over orders of magnitudes

# 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 ...

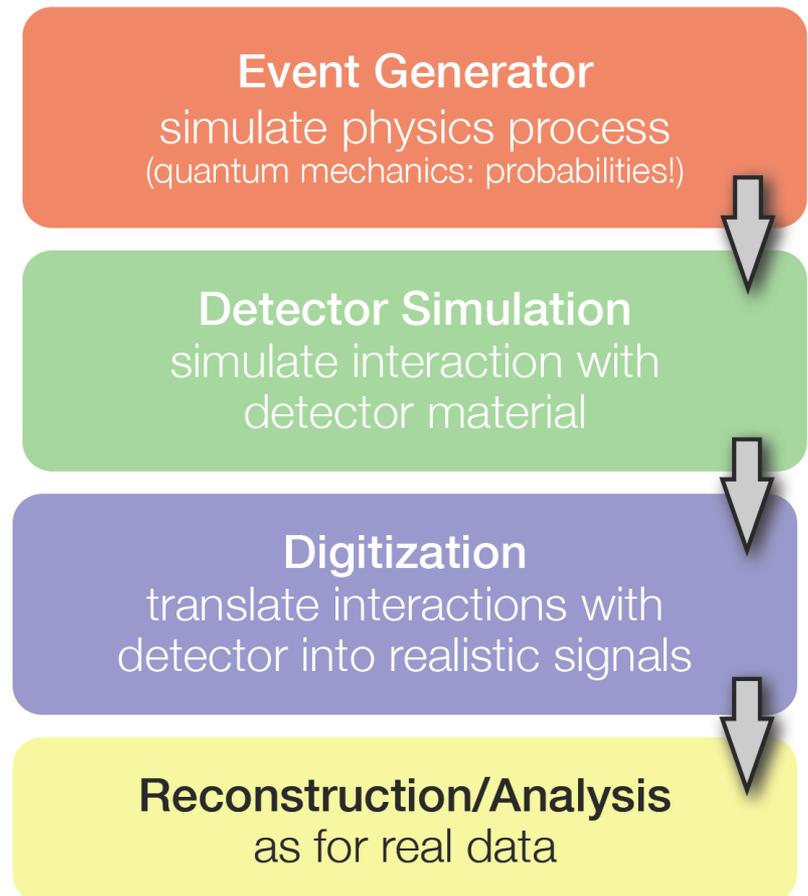
Hard partonic subprocess +  
fragmentation & hadronization ...

Detector simulation:

Geant ...

interaction & response  
of all produced particles ...

## MC simulations in particle physics



# Pythia sub-processes

|   |   |  |   |  |   |   |
|---|---|--|---|--|---|---|
| No. Subprocess                                  | No. Subprocess  | No. Subprocess                                     | No. Subprocess  | No. Subprocess   | No. Subprocess  | No. Subprocess  |
| Hard QCD processes:                             | 36 $f_i \gamma \rightarrow f_k W^\pm$                               | New gauge bosons:                                  | Higgs pairs:  | Compositeness:   | 210 $f_i \bar{f}_j \rightarrow \tilde{\ell}_L \tilde{\nu}_\ell^* +$   | 250 $f_i g \rightarrow \tilde{q}_L \tilde{\chi}_3$            |
| 11 $f_i \bar{f}_j \rightarrow f_k \bar{f}_l$    | 69 $\gamma \gamma \rightarrow W^+ W^-$                              | 141 $f_i \bar{f}_i \rightarrow \gamma / Z^0 / Z^0$ | 297 $f_i \bar{f}_j \rightarrow H^\pm h^0$               | 146 $e \gamma \rightarrow e^*$   | 211 $f_i \bar{f}_j \rightarrow \tilde{\tau}_1 \tilde{\nu}_\tau^* +$   | 251 $f_i g \rightarrow \tilde{q}_R \tilde{\chi}_3$            |
| 12 $f_i \bar{f}_i \rightarrow f_k \bar{f}_k$    | 70 $\gamma W^\pm \rightarrow Z^0 W^\pm$                             | 142 $f_i \bar{f}_j \rightarrow W^{+\pm}$           | 298 $f_i \bar{f}_j \rightarrow H^\pm H^0$               | 147 $d g \rightarrow d^*$  | 212 $f_i \bar{f}_j \rightarrow \tilde{\tau}_2 \tilde{\nu}_\tau^* +$   | 252 $f_i g \rightarrow \tilde{q}_L \tilde{\chi}_4$            |
| 13 $f_i \bar{f}_i \rightarrow g g$              | Prompt photons:   | 144 $f_i \bar{f}_j \rightarrow R$                  | 299 $f_i \bar{f}_i \rightarrow A^0 h^0$                 | 148 $u g \rightarrow u^*$  | 213 $f_i \bar{f}_i \rightarrow \tilde{\nu}_\ell \tilde{\nu}_\ell^* +$ | 253 $f_i g \rightarrow \tilde{q}_R \tilde{\chi}_4$            |
| 28 $f_i g \rightarrow f_i g$                    | 14 $f_i \bar{f}_i \rightarrow g \gamma$                             | Heavy SM Higgs:                                    | 300 $f_i \bar{f}_i \rightarrow A^0 H^0$                 | 167 $q_i q_j \rightarrow d^* q_k$  | 214 $f_i \bar{f}_i \rightarrow \tilde{\nu}_\tau \tilde{\nu}_\tau^* +$ | 254 $f_i g \rightarrow \tilde{q}_J L \tilde{\chi}_1^\pm$      |
| 53 $g g \rightarrow f_k \bar{f}_k$              | 18 $f_i \bar{f}_i \rightarrow \gamma \gamma$                        | 5 $Z^0 Z^0 \rightarrow h^0$                        | 301 $f_i \bar{f}_i \rightarrow H^+ H^-$                 | 168 $q_i q_j \rightarrow u^* q_k$  | 216 $f_i \bar{f}_i \rightarrow \tilde{\chi}_1 \tilde{\chi}_1$         | 256 $f_i g \rightarrow \tilde{q}_J L \tilde{\chi}_2^\pm$      |
| 68 $g g \rightarrow g g$                        | 29 $f_i g \rightarrow f_i \gamma$                                   | 8 $W^+ W^- \rightarrow h^0$                        | Leptoquarks:  | 169 $q_i \bar{q}_j \rightarrow e^\pm e^{*\mp}$                             | 217 $f_i \bar{f}_i \rightarrow \tilde{\chi}_2 \tilde{\chi}_2$         | 258 $f_i g \rightarrow \tilde{q}_L \tilde{g}$                 |
| Soft QCD processes:                             | 114 $g g \rightarrow \gamma \gamma$                                 | 71 $Z_L^0 Z_L^0 \rightarrow Z_L^0 Z_L^0$           | 145 $q_i \ell_j \rightarrow L_Q$                        | 165 $f_i \bar{f}_i (\rightarrow \gamma^* / Z^0) \rightarrow f_k \bar{f}_k$ | 218 $f_i \bar{f}_i \rightarrow \tilde{\chi}_3 \tilde{\chi}_3$         | 259 $f_i g \rightarrow \tilde{q}_R \tilde{g}$                 |
| 91 elastic scattering                           | 115 $g g \rightarrow g \gamma$                                      | 72 $Z_L^0 Z_L^0 \rightarrow W_L^+ W_L^-$           | 162 $q g \rightarrow \ell L_Q$                          | 166 $f_i \bar{f}_j (\rightarrow W^\pm) \rightarrow f_k \bar{f}_l$          | 219 $f_i \bar{f}_i \rightarrow \tilde{\chi}_4 \tilde{\chi}_4$         | 261 $f_i \bar{f}_i \rightarrow \tilde{t}_1 \tilde{t}_1$       |
| 92 single diffraction ( $X B$ )                 | Deeply Inel. Scatt.:  | 73 $Z_L^0 W_L^\pm \rightarrow Z_L^0 W_L^\pm$       | 163 $g g \rightarrow L_Q \bar{L}_Q$                     | Extra Dimensions:  | 220 $f_i \bar{f}_i \rightarrow \tilde{\chi}_1 \tilde{\chi}_2$         | 262 $f_i \bar{f}_i \rightarrow \tilde{t}_2 \tilde{t}_2^*$     |
| 93 single diffraction ( $A X$ )                 | 10 $f_i \bar{f}_j \rightarrow f_k \bar{f}_l$                        | 76 $W_L^+ W_L^- \rightarrow Z_L^0 Z_L^0$           | 164 $q_i \bar{q}_i \rightarrow L_Q \bar{L}_Q$           | 391 $f \bar{f} \rightarrow G^*$  | 221 $f_i \bar{f}_i \rightarrow \tilde{\chi}_1 \tilde{\chi}_3$         | 263 $f_i \bar{f}_i \rightarrow \tilde{t}_1 \tilde{t}_2^* +$   |
| 94 double diffraction                           | 99 $\gamma^* q \rightarrow q$                                       | 77 $W_L^\pm W_L^\pm \rightarrow W_L^\pm W_L^\pm$   | Technicolor:  | 392 $g g \rightarrow G^*$  | 222 $f_i \bar{f}_i \rightarrow \tilde{\chi}_1 \tilde{\chi}_4$         | 264 $g g \rightarrow \tilde{t}_1 \tilde{t}_1^*$               |
| 95 low- $p_\perp$ production                    | Photon-induced:   | BSM Neutral Higgs:                                 | 149 $g g \rightarrow \eta_{tc}$                         | 393 $q \bar{q} \rightarrow G^*$  | 223 $f_i \bar{f}_i \rightarrow \tilde{\chi}_2 \tilde{\chi}_3$         | 265 $g g \rightarrow \tilde{t}_2 \tilde{t}_2^*$               |
| Open heavy flavour:<br>(also fourth generation) | 33 $f_i \gamma \rightarrow f_i g$                                   | 151 $f_i \bar{f}_i \rightarrow H^0$                | 191 $f_i \bar{f}_i \rightarrow \rho_{tc}^0$             | 394 $q g \rightarrow q G^*$  | 224 $f_i \bar{f}_i \rightarrow \tilde{\chi}_2 \tilde{\chi}_4$         | 271 $f_i \bar{f}_j \rightarrow \tilde{q}_L \tilde{q}_J L$     |
| 81 $f_i \bar{f}_i \rightarrow Q_k \bar{Q}_k$    | 34 $f_i \gamma \rightarrow f_i \gamma$                              | 152 $g g \rightarrow H^0$                          | 192 $f_i \bar{f}_j \rightarrow \rho_{tc}^+$             | 395 $g g \rightarrow g G^*$  | 225 $f_i \bar{f}_i \rightarrow \tilde{\chi}_3 \tilde{\chi}_4$         | 272 $f_i \bar{f}_j \rightarrow \tilde{q}_R \tilde{q}_J R$     |
| 82 $g g \rightarrow Q_k \bar{Q}_k$              | 54 $g \gamma \rightarrow f_k \bar{f}_k$                             | 153 $\gamma \gamma \rightarrow H^0$                | 193 $f_i \bar{f}_i \rightarrow \omega_{tc}^0$           | Left-right symmetry:   | 226 $f_i \bar{f}_i \rightarrow \tilde{\chi}_1^\pm \tilde{\chi}_1^\mp$ | 273 $f_i \bar{f}_j \rightarrow \tilde{q}_L \tilde{q}_J R +$   |
| 83 $q_i \bar{f}_j \rightarrow Q_k \bar{f}_l$    | 58 $\gamma \gamma \rightarrow f_k \bar{f}_k$                        | 171 $f_i \bar{f}_i \rightarrow Z^0 H^0$            | 194 $f_i \bar{f}_i \rightarrow f_k \bar{f}_k$           | 341 $\ell_i \ell_j \rightarrow H_L^{\pm\pm}$                               | 227 $f_i \bar{f}_i \rightarrow \tilde{\chi}_2^\pm \tilde{\chi}_2^\mp$ | 274 $f_i \bar{f}_j \rightarrow \tilde{q}_L \tilde{q}_J^* L$   |
| 84 $g \gamma \rightarrow Q_k \bar{Q}_k$         | 131 $f_i \gamma \tilde{T} \rightarrow f_i g$                        | 172 $f_i \bar{f}_j \rightarrow W^\pm H^0$          | 195 $f_i \bar{f}_j \rightarrow f_k \bar{f}_l$           | 342 $\ell_i \ell_j \rightarrow H_R^{\pm\pm}$                               | 228 $f_i \bar{f}_i \rightarrow \tilde{\chi}_1^\pm \tilde{\chi}_2^\mp$ | 275 $f_i \bar{f}_j \rightarrow \tilde{q}_R \tilde{q}_J^* R$   |
| 85 $\gamma \gamma \rightarrow F_k \bar{F}_k$    | 132 $f_i \gamma \tilde{L} \rightarrow f_i g$                        | 173 $f_i \bar{f}_j \rightarrow f_i f_j H^0$        | 361 $f_i \bar{f}_i \rightarrow W_L^+ W_L^-$             | 343 $\ell_i^\pm \gamma \rightarrow H_L^{\pm\pm} e^\mp$                     | 229 $f_i \bar{f}_j \rightarrow \tilde{\chi}_1 \tilde{\chi}_1^\pm$     | 276 $f_i \bar{f}_j \rightarrow \tilde{q}_L \tilde{q}_J^* R +$ |
| Closed heavy flavour:                           | 133 $f_i \gamma \tilde{T} \rightarrow f_i \gamma$                   | 174 $f_i \bar{f}_j \rightarrow f_k \bar{f}_l H^0$  | 362 $f_i \bar{f}_i \rightarrow W_L^\pm \pi_{tc}^\mp$    | 344 $\ell_i^\pm \gamma \rightarrow H_L^{\pm\pm} e^\mp$                     | 230 $f_i \bar{f}_j \rightarrow \tilde{\chi}_2 \tilde{\chi}_1^\pm$     | 277 $f_i \bar{f}_i \rightarrow \tilde{q}_J L \tilde{q}_J^* L$ |
| 86 $g g \rightarrow J/\psi g$                   | 134 $f_i \gamma \tilde{L} \rightarrow f_i \gamma$                   | 181 $g g \rightarrow Q_k \bar{Q}_k H^0$            | 363 $f_i \bar{f}_i \rightarrow \pi_{tc}^+ \pi_{tc}^-$   | 345 $\ell_i^\pm \gamma \rightarrow H_R^{\pm\pm} \mu^\mp$                   | 231 $f_i \bar{f}_j \rightarrow \tilde{\chi}_3 \tilde{\chi}_1^\pm$     | 278 $f_i \bar{f}_i \rightarrow \tilde{q}_J R \tilde{q}_J^* R$ |
| 87 $g g \rightarrow \chi_{0c} g$                | 135 $g \gamma \tilde{T} \rightarrow f_i \bar{f}_i$                  | 182 $q_i \bar{q}_i \rightarrow Q_k \bar{Q}_k H^0$  | 364 $f_i \bar{f}_i \rightarrow \gamma \pi_{tc}^0$       | 346 $\ell_i^\pm \gamma \rightarrow H_R^{\pm\pm} \mu^\mp$                   | 232 $f_i \bar{f}_j \rightarrow \tilde{\chi}_4 \tilde{\chi}_1^\pm$     | 279 $g g \rightarrow \tilde{q}_L \tilde{q}_L^* L$             |
| 88 $g g \rightarrow \chi_{1c} g$                | 136 $g \gamma \tilde{L} \rightarrow f_i \bar{f}_i$                  | 183 $f_i \bar{f}_i \rightarrow g H^0$              | 365 $f_i \bar{f}_i \rightarrow \gamma \pi_{tc}^{*0}$    | 347 $\ell_i^\pm \gamma \rightarrow H_L^{\pm\pm} \tau^\mp$                  | 233 $f_i \bar{f}_j \rightarrow \tilde{\chi}_1 \tilde{\chi}_2^\pm$     | 280 $g g \rightarrow \tilde{q}_R \tilde{q}_R^* R$             |
| 89 $g g \rightarrow \chi_{2c} g$                | 137 $\gamma \tilde{T}^* \gamma \tilde{T} \rightarrow f_i \bar{f}_i$ | 184 $f_i g \rightarrow f_i H^0$                    | 366 $f_i \bar{f}_i \rightarrow Z^0 \pi_{tc}^{*0}$       | 348 $\ell_i^\pm \gamma \rightarrow H_R^{\pm\pm} \tau^\mp$                  | 234 $f_i \bar{f}_j \rightarrow \tilde{\chi}_2 \tilde{\chi}_2^\pm$     | 281 $b q_i \rightarrow \tilde{b}_1 \tilde{q}_L$               |
| 104 $g g \rightarrow \chi_{0c}$                 | 138 $\gamma \tilde{T}^* \gamma \tilde{L} \rightarrow f_i \bar{f}_i$ | 185 $g g \rightarrow g H^0$                        | 367 $f_i \bar{f}_i \rightarrow Z^0 \pi_{tc}^{*0}$       | 349 $f_i \bar{f}_i \rightarrow H_L^{++} H_L^{--}$                          | 235 $f_i \bar{f}_j \rightarrow \tilde{\chi}_3 \tilde{\chi}_2^\pm$     | 282 $b q_i \rightarrow \tilde{b}_2 \tilde{q}_R$               |
| 105 $g g \rightarrow \chi_{2c}$                 | 139 $\gamma \tilde{L}^* \gamma \tilde{T} \rightarrow f_i \bar{f}_i$ | 156 $f_i \bar{f}_i \rightarrow A^0$                | 368 $f_i \bar{f}_i \rightarrow W^\pm \pi_{tc}^\mp$      | 350 $f_i \bar{f}_i \rightarrow H_R^{++} H_R^{--}$                          | 236 $f_i \bar{f}_j \rightarrow \tilde{\chi}_4 \tilde{\chi}_2^\pm$     | 283 $b q_i \rightarrow \tilde{b}_1 \tilde{q}_R +$             |
| 106 $g g \rightarrow J/\psi \gamma$             | 140 $\gamma \tilde{L}^* \gamma \tilde{L} \rightarrow f_i \bar{f}_i$ | 157 $g g \rightarrow A^0$                          | 370 $f_i \bar{f}_j \rightarrow W_L^\pm Z_L^0$           | 351 $f_i \bar{f}_j \rightarrow f_k \bar{f}_l H_L^{\pm\pm}$                 | 237 $f_i \bar{f}_i \rightarrow \tilde{g} \tilde{\chi}_1$              | 284 $b \bar{q}_i \rightarrow \tilde{b}_1 \tilde{q}_L^*$       |
| 107 $g \gamma \rightarrow J/\psi g$             | 80 $q_i \gamma \rightarrow q_k \pi^\pm$                             | 158 $\gamma \gamma \rightarrow A^0$                | 371 $f_i \bar{f}_j \rightarrow W_L^\pm \pi_{tc}^0$      | 352 $f_i \bar{f}_j \rightarrow f_k \bar{f}_l H_R^{\pm\pm}$                 | 238 $f_i \bar{f}_i \rightarrow \tilde{g} \tilde{\chi}_2$              | 285 $b \bar{q}_i \rightarrow \tilde{b}_2 \tilde{q}_R^*$       |
| 108 $\gamma \gamma \rightarrow J/\psi \gamma$   | Light SM Higgs:   | 176 $f_i \bar{f}_i \rightarrow Z^0 A^0$            | 372 $f_i \bar{f}_j \rightarrow \pi_{tc}^\pm Z_L^0$      | 353 $f_i \bar{f}_i \rightarrow Z^0 R$                                      | 239 $f_i \bar{f}_i \rightarrow \tilde{g} \tilde{\chi}_3$              | 286 $b \bar{q}_i \rightarrow \tilde{b}_1 \tilde{q}_R^* R +$   |
| W/Z production:                                 | 3 $f_i \bar{f}_i \rightarrow h^0$                                   | 177 $f_i \bar{f}_j \rightarrow W^\pm A^0$          | 373 $f_i \bar{f}_j \rightarrow \pi_{tc}^\pm \pi_{tc}^0$ | 354 $f_i \bar{f}_j \rightarrow W_R^\pm$                                    | 240 $f_i \bar{f}_i \rightarrow \tilde{g} \tilde{\chi}_4$              | 287 $f_i \bar{f}_i \rightarrow \tilde{b}_1 \tilde{b}_1^*$     |
| 1 $f_i \bar{f}_i \rightarrow \gamma^* / Z^0$    | 24 $f_i \bar{f}_i \rightarrow Z^0 h^0$                              | 178 $f_i \bar{f}_j \rightarrow f_i f_j A^0$        | 374 $f_i \bar{f}_j \rightarrow \gamma \pi_{tc}^\pm$     | SUSY:  | 241 $f_i \bar{f}_j \rightarrow \tilde{g} \tilde{\chi}_1^\pm$          | 288 $f_i \bar{f}_i \rightarrow \tilde{b}_2 \tilde{b}_2^*$     |
| 2 $f_i \bar{f}_j \rightarrow W^\pm$             | 26 $f_i \bar{f}_j \rightarrow W^\pm h^0$                            | 179 $f_i \bar{f}_j \rightarrow f_k \bar{f}_l A^0$  | 375 $f_i \bar{f}_j \rightarrow Z^0 \pi_{tc}^\pm$        | 201 $f_i \bar{f}_i \rightarrow \tilde{\ell}_L \tilde{\ell}_L^*$            | 242 $f_i \bar{f}_j \rightarrow \tilde{g} \tilde{\chi}_2^\pm$          | 289 $g g \rightarrow \tilde{b}_1 \tilde{b}_1^*$               |
| 22 $f_i \bar{f}_i \rightarrow Z^0 Z^0$          | 32 $f_i g \rightarrow f_i h^0$                                      | 186 $g g \rightarrow Q_k \bar{Q}_k A^0$            | 376 $f_i \bar{f}_j \rightarrow W^\pm \pi_{tc}^0$        | 202 $f_i \bar{f}_i \rightarrow \tilde{e}_R \tilde{e}_R^*$                  | 243 $f_i \bar{f}_i \rightarrow \tilde{g} \tilde{g}$                   | 290 $g g \rightarrow \tilde{b}_2 \tilde{b}_2^*$               |
| 23 $f_i \bar{f}_j \rightarrow Z^0 W^\pm$        | 102 $g g \rightarrow h^0$   | 187 $q_i \bar{q}_i \rightarrow Q_k \bar{Q}_k A^0$  | 377 $f_i \bar{f}_j \rightarrow W^\pm \pi_{tc}^{*0}$     | 203 $f_i \bar{f}_i \rightarrow \tilde{e}_L \tilde{e}_R^* +$                | 244 $g g \rightarrow \tilde{g} \tilde{g}$                             | 291 $bb \rightarrow \tilde{b}_1 \tilde{b}_1$                  |
| 25 $f_i \bar{f}_i \rightarrow W^+ W^-$          | 103 $\gamma \gamma \rightarrow h^0$                                 | 188 $f_i \bar{f}_i \rightarrow g A^0$              | 381 $q_i q_j \rightarrow q_i q_j$                       | 204 $f_i \bar{f}_i \rightarrow \tilde{\mu}_L \tilde{\mu}_L^*$              | 246 $f_i g \rightarrow \tilde{q}_L \tilde{\chi}_1$                    | 292 $bb \rightarrow \tilde{b}_2 \tilde{b}_2$                  |
| 15 $f_i \bar{f}_i \rightarrow g Z^0$            | 110 $f_i \bar{f}_i \rightarrow \gamma h^0$                          | 189 $f_i g \rightarrow f_i A^0$                    | 382 $q_i \bar{q}_i \rightarrow q_k \bar{q}_k$           | 205 $f_i \bar{f}_i \rightarrow \tilde{\mu}_R \tilde{\mu}_R^* +$            | 247 $f_i g \rightarrow \tilde{q}_R \tilde{\chi}_1$                    | 293 $bb \rightarrow \tilde{b}_1 \tilde{b}_2$                  |
| 16 $f_i \bar{f}_j \rightarrow g W^\pm$          | 111 $f_i \bar{f}_i \rightarrow g h^0$                               | 190 $g g \rightarrow g A^0$                        | 383 $q_i \bar{q}_i \rightarrow g g$                     | 206 $f_i \bar{f}_i \rightarrow \tilde{\mu}_L \tilde{\mu}_R^* +$            | 248 $f_i g \rightarrow \tilde{q}_L \tilde{\chi}_2$                    | 294 $bg \rightarrow \tilde{b}_1 \tilde{g}$                    |
| 30 $f_i g \rightarrow f_i Z^0$                  | 112 $f_i g \rightarrow f_i h^0$                                     | Charged Higgs:                                     | 384 $f_i g \rightarrow f_i g$                           | 207 $f_i \bar{f}_i \rightarrow \tilde{\tau}_1 \tilde{\tau}_1^*$            | 249 $f_i g \rightarrow \tilde{q}_R \tilde{\chi}_2$                    | 295 $bg \rightarrow \tilde{b}_2 \tilde{g}$                    |
| 31 $f_i g \rightarrow f_k W^\pm$                | 113 $g g \rightarrow g h^0$   | 143 $f_i \bar{f}_j \rightarrow H^+$                | 385 $g g \rightarrow q_k \bar{q}_k$                     | 208 $f_i \bar{f}_i \rightarrow \tilde{\tau}_2 \tilde{\tau}_2^*$            |   | 296 $bb \rightarrow \tilde{b}_1 \tilde{b}_2^* +$              |
| 19 $f_i \bar{f}_i \rightarrow \gamma Z^0$       | 121 $g g \rightarrow Q_k \bar{Q}_k h^0$                             | 161 $f_i g \rightarrow f_k H^+$                    | 386 $g g \rightarrow g g$                               | 209 $f_i \bar{f}_i \rightarrow \tilde{\tau}_1 \tilde{\tau}_2^* +$          |   |   |
| 20 $f_i \bar{f}_j \rightarrow \gamma W^\pm$     | 122 $q_i \bar{q}_i \rightarrow Q_k \bar{Q}_k h^0$                   | 401 $g g \rightarrow \tilde{t} b H^+$              | 387 $f_i \bar{f}_i \rightarrow Q_k \bar{Q}_k$           |  |   |   |
| 35 $f_i \gamma \rightarrow f_i Z^0$             | 123 $f_i \bar{f}_j \rightarrow f_i f_j h^0$                         | 402 $q \bar{q} \rightarrow \tilde{t} b H^+$        | 388 $g g \rightarrow Q_k \bar{Q}_k$                     |  |   |   |

# 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:

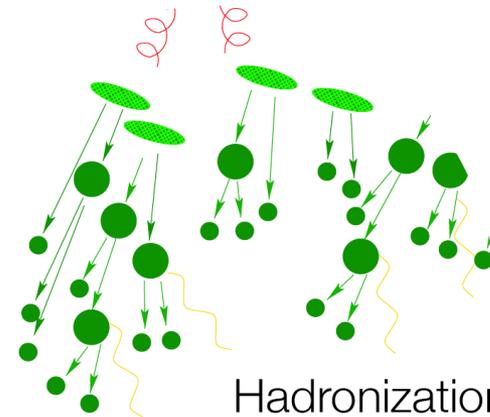
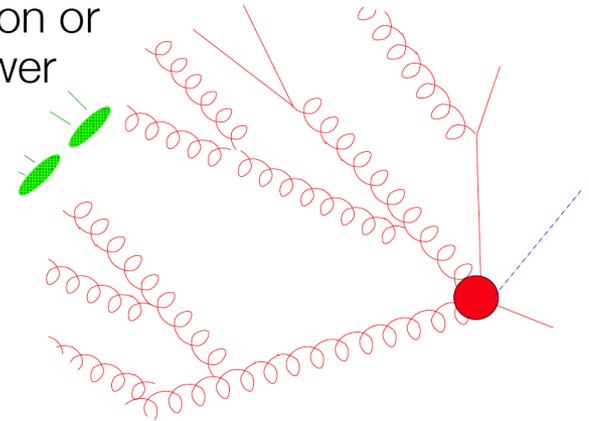
Parton shower forms hadrons

[non-perturbative, only models]

**Decay** of unstable hadrons

[perturbative QCD, electroweak theory]

Fragmentation or Parton Shower



Hadronization & Decays

# Detector simulation

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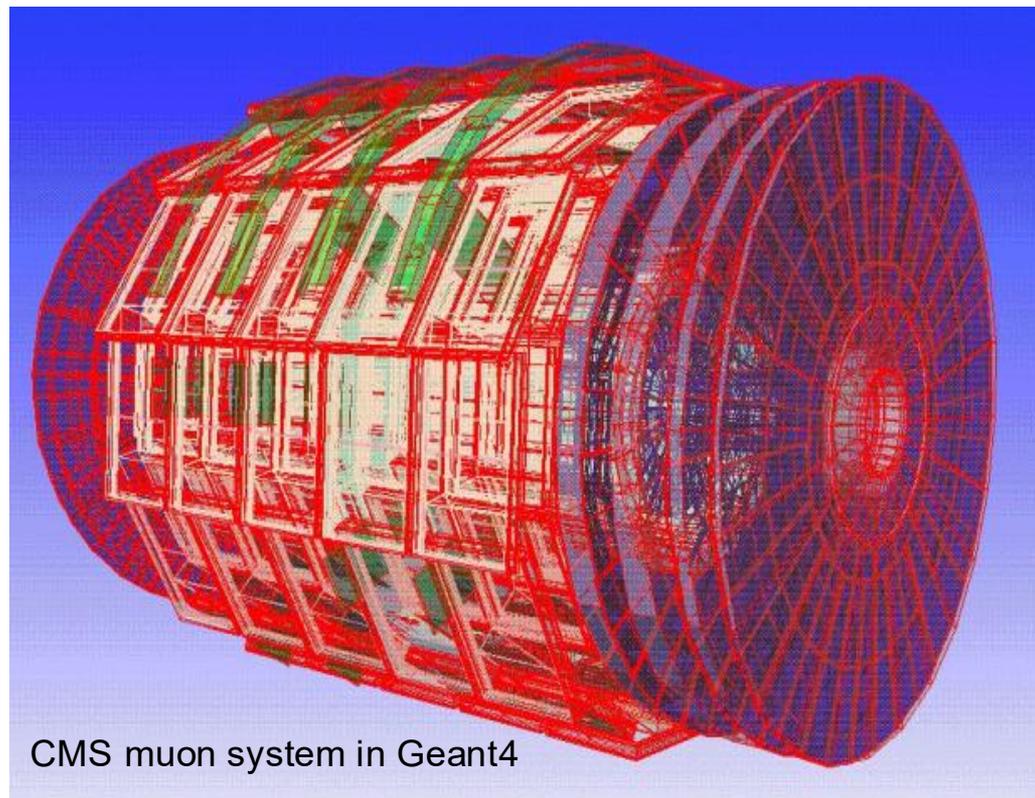
## GEANT

Geometry And Tracking

Detailed description of detector **geometry**  
[sensitive & insensitive volumes]

**Tracking** of all particles through detector material ...

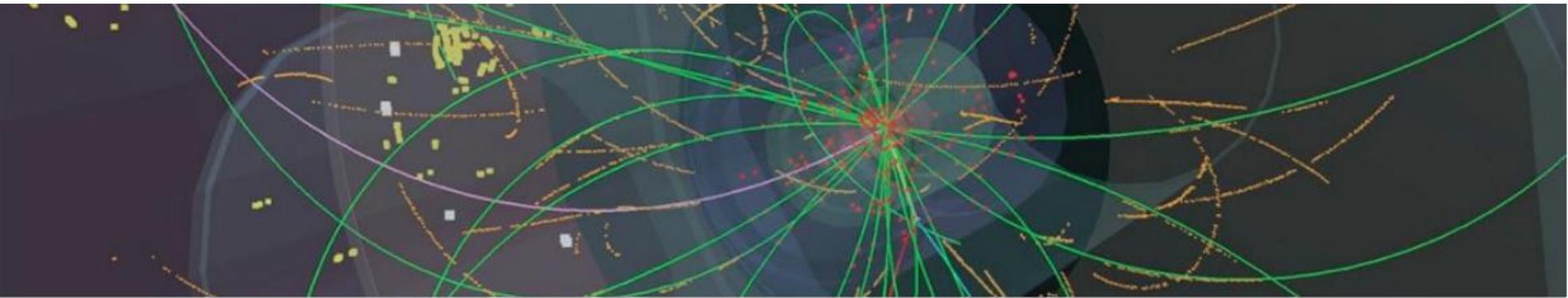
→ **Detector response**



Developed at CERN since 1974 (FORTRAN)

[Today: Geant4; programmed in C++]

# Luminosity and cross-section measurements



# Cross section & Luminosity

---

**Number of observed events**

just count ...

**Background**

measured from data or  
calculated from theory

$$\sigma = \frac{N^{\text{obs}} - N^{\text{bkg}}}{\int \mathcal{L} dt \cdot \epsilon}$$

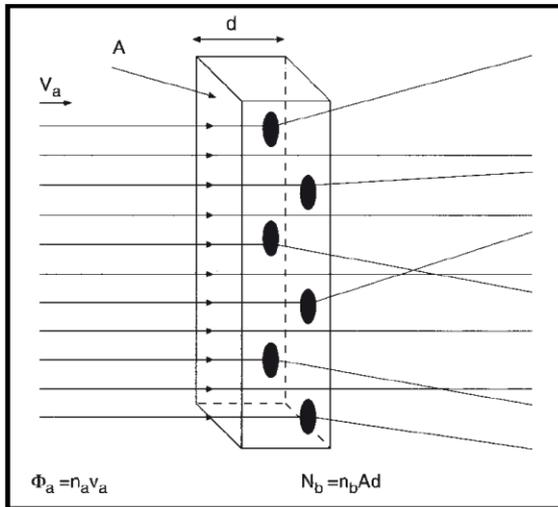
**Luminosity**

determined by accelerator,  
triggers, ...

**Efficiency**

many factors, optimized  
by experimentalist

# Cross section & Luminosity



$$\dot{N} \equiv L \cdot \sigma$$

$$N = \sigma \cdot \underbrace{\int L dt}_{\text{integrated luminosity}} \quad \sigma = N/L$$

Collider experiment:

$$\Phi_a = \frac{\dot{N}_a}{A} = \frac{N_a \cdot n \cdot v/U}{A} = \frac{N_a \cdot n \cdot f}{A}$$

$$L = f \frac{n N_a N_b}{A} = f \frac{n N_a N_b}{4\pi\sigma_x\sigma_y}$$

$$\Phi_a = \frac{\dot{N}_a}{A} = n_a v_a$$

$\Phi_a$ : flux  
 $n_a$ : density of particle beam  
 $v_a$ : velocity of beam particles

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

$\dot{N}$ : reaction rate  
 $N_b$ : target particles within beam area  
 $\sigma_a$ : effective area of single scattering center

$$L = \Phi_a \cdot N_b$$

L : luminosity

LHC:

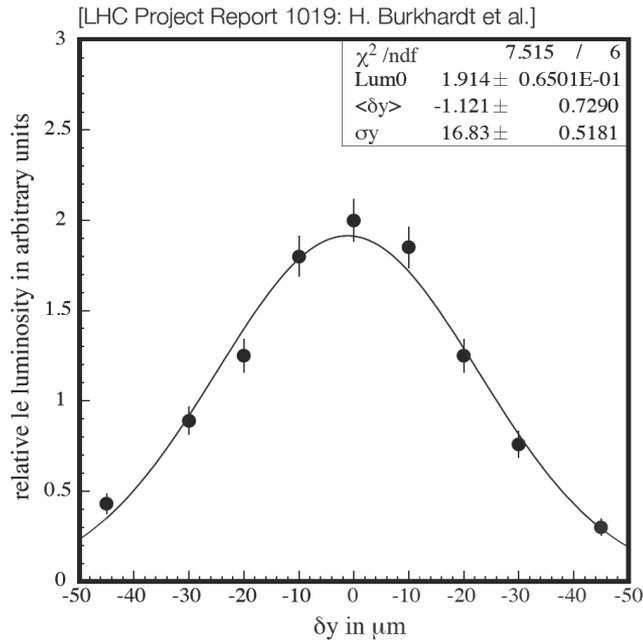
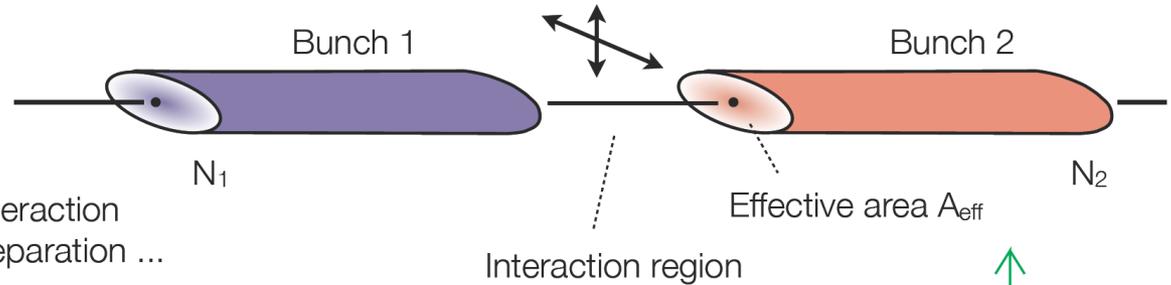
|       |   |
|-------|---|
| $N_x$ | $\sim 10^{11}$                                |
| A     | $\sim .0005 \text{ mm}^2$                     |
| n     | $\sim 2800$                                   |
| f     | $\sim 11 \text{ kHz}$                         |
| L     | $\sim 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ |

$N_a$ : number of particles per bunch (beam A)  
 $N_b$ : number of particles per bunch (beam B)  
U : circumference of ring  
n : number of bunches per beam  
v : velocity of beam particles  
f : revolution frequency  
A : beam cross-section  
 $\sigma_x$ : standard deviation of beam profile in x  
 $\sigma_y$ : standard deviation of beam profile in y

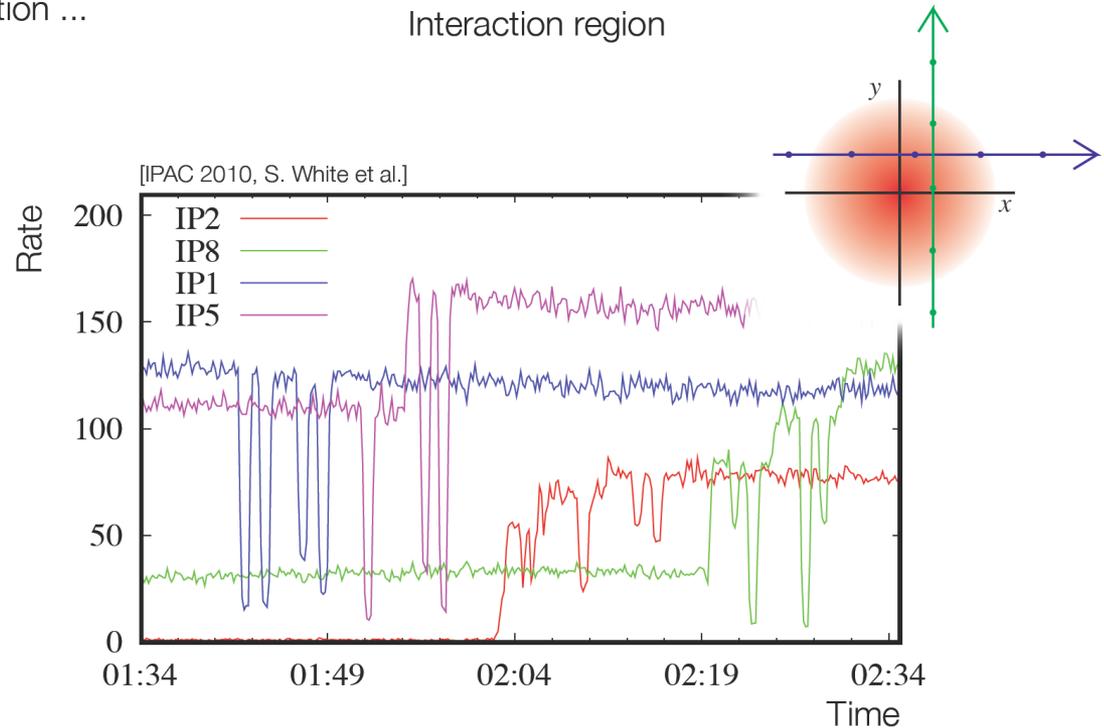
# Van-der-Meer separation scan

Determine beam size ...

measuring size and shape of the interaction region by recording relative interaction rates as a function of transverse beam separation ...

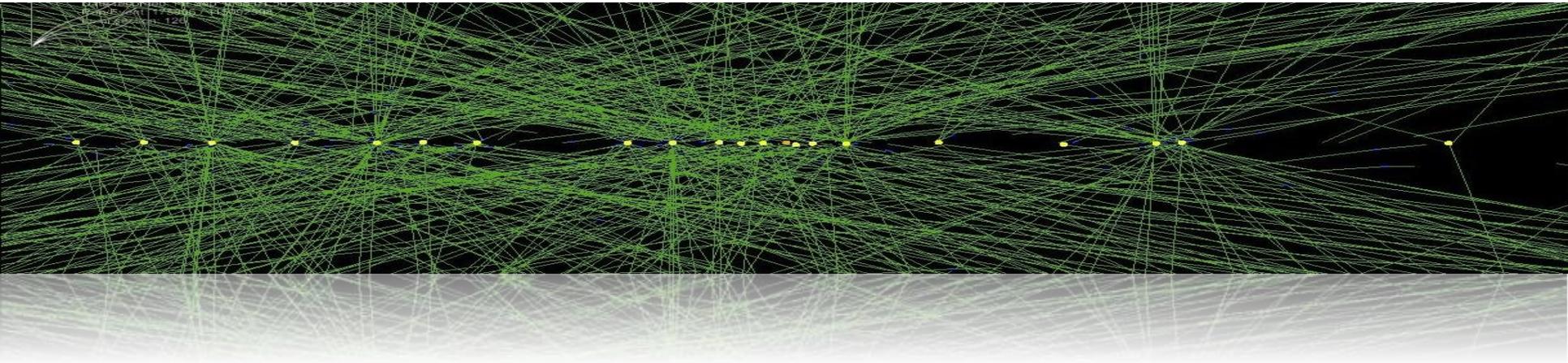


$$\frac{L}{L_0} = \exp \left[ - \left( \frac{\delta_x}{2\sigma_x} \right)^2 - \left( \frac{\delta_y}{2\sigma_y} \right)^2 \right]$$



First optimization scans at LHC performed for squeezed optics in all IPs [November 2009].

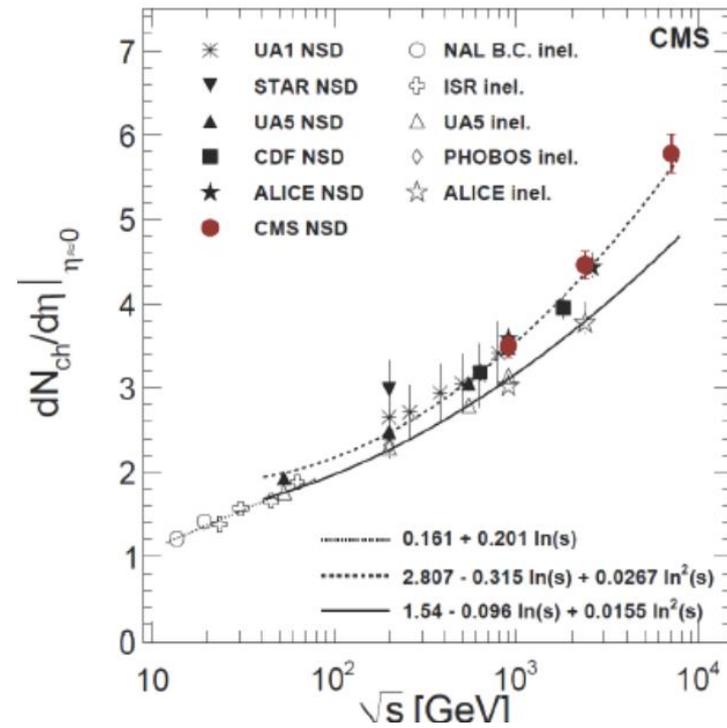
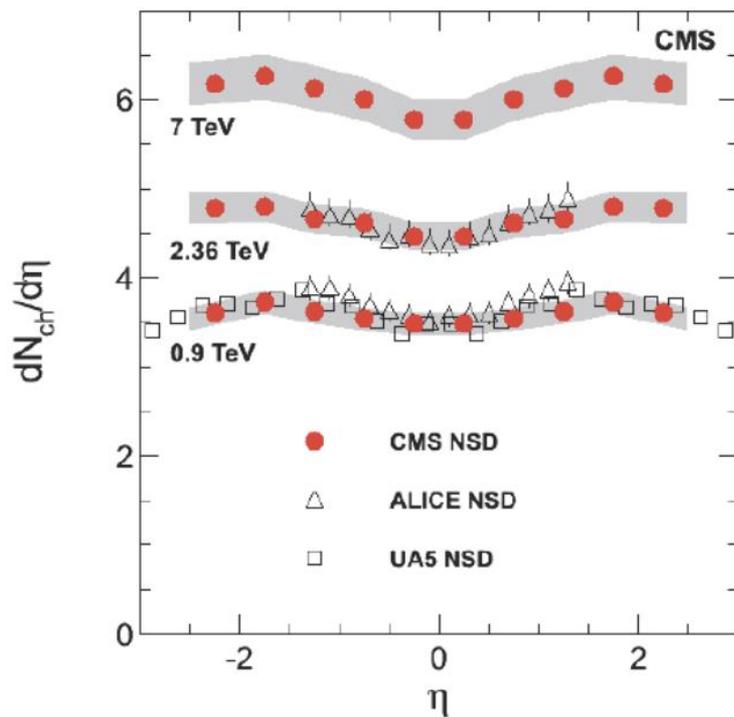
# Minimum bias events



# Characteristics of inelastic p-p collisions

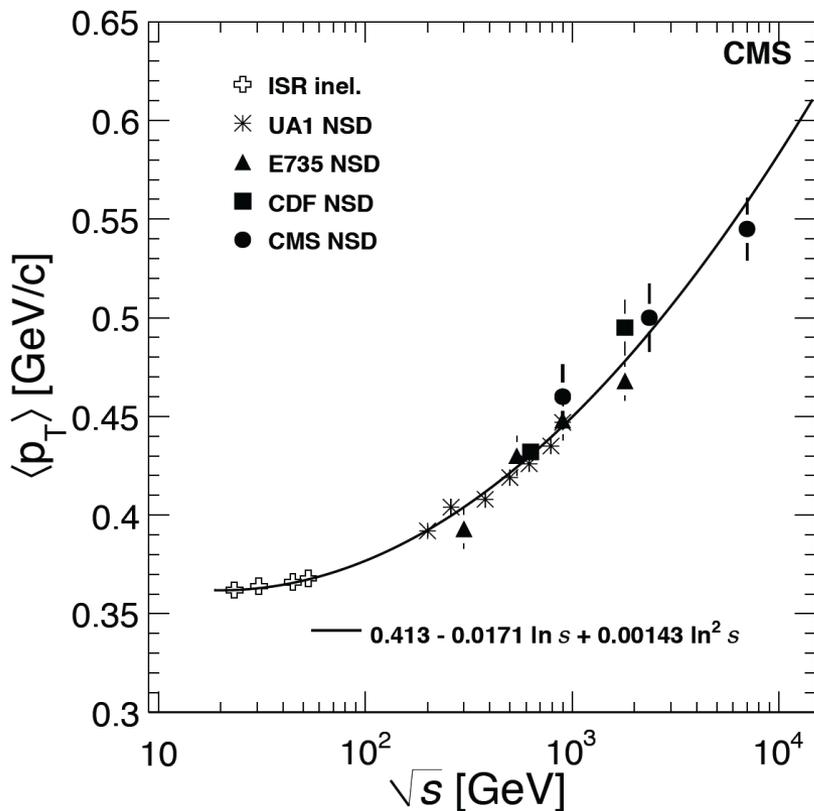
Particle density in minimum bias events

Soft QCD (PT threshold on tracks: 50 MeV)

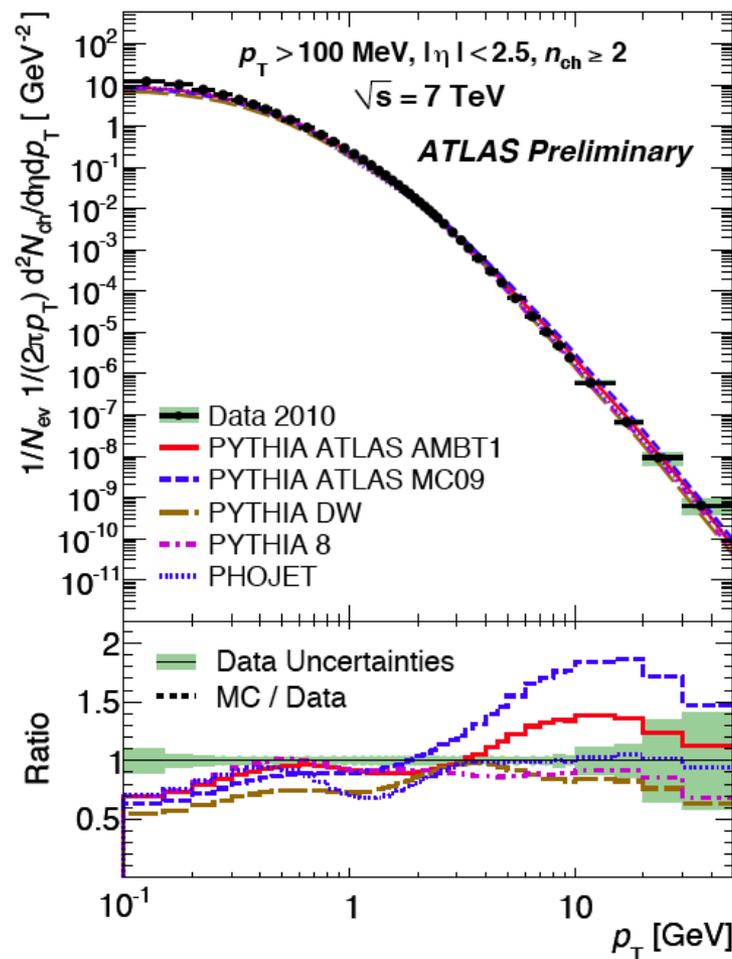


# Charged particle $p_T$ spectrum

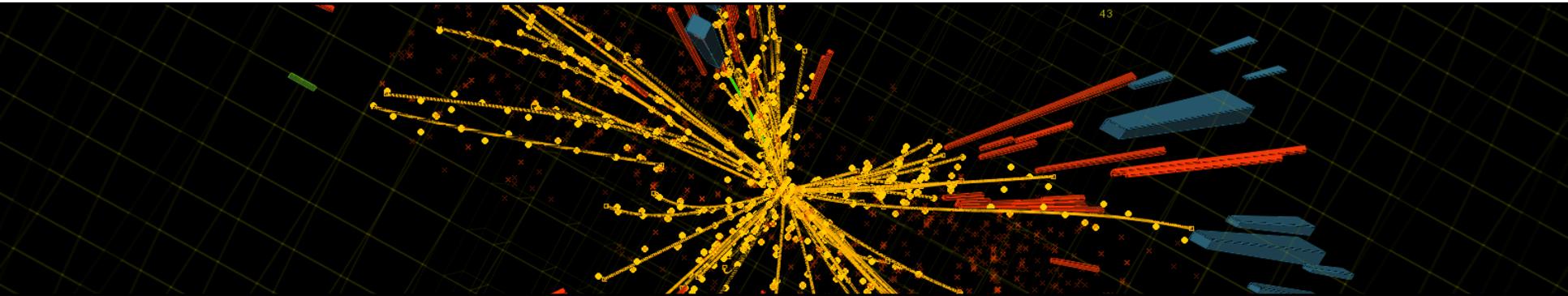
$\langle p_T \rangle = 0.545$   
 $\pm 0.005$  (stat.)  
 $\pm 0.015$  (syst.) GeV/c



$dN_{ch}/dp_T$   
 $p_T > 100$  MeV  
 $|\eta| < 2.5$   
 $N_{ch} \geq 2$

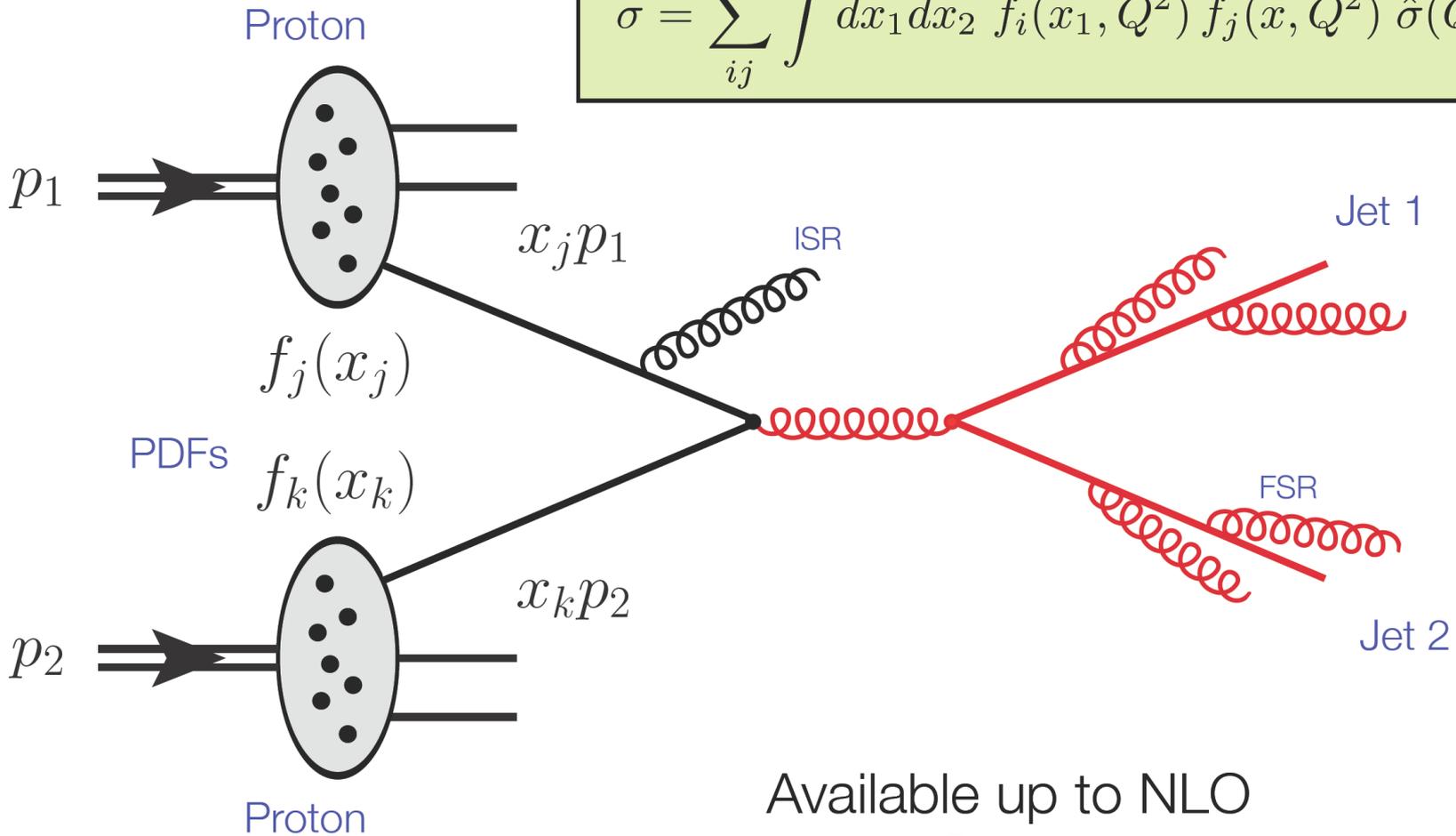


# Jet physics



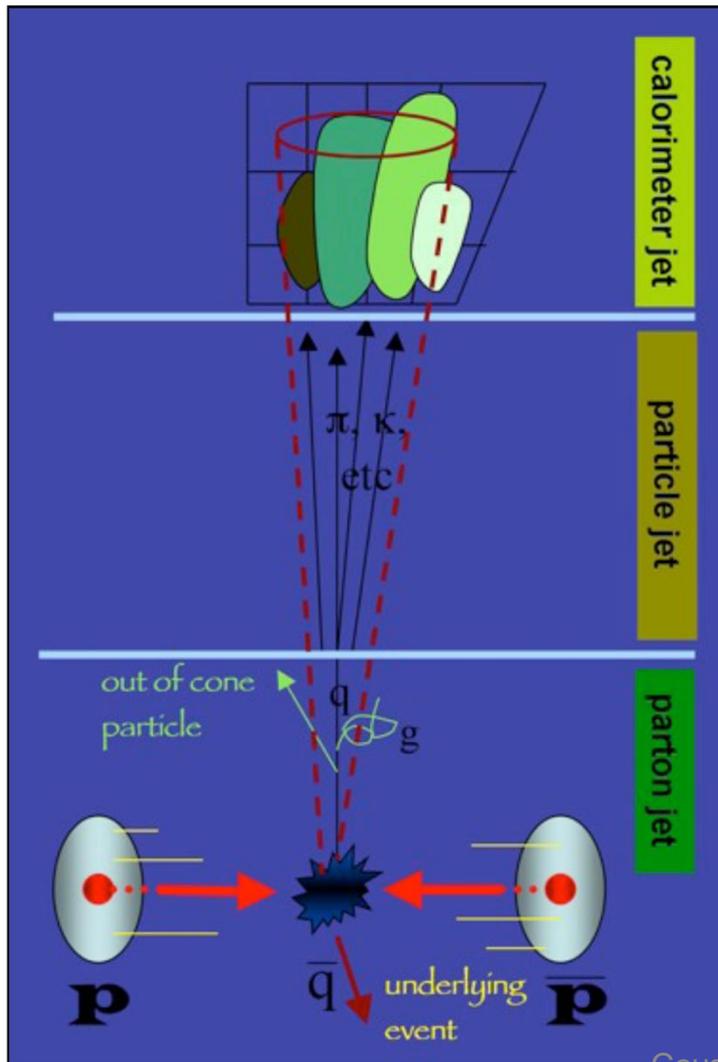
# Jet production @ LHC

$$\sigma = \sum_{ij} \int dx_1 dx_2 f_i(x_1, Q^2) f_j(x_2, Q^2) \hat{\sigma}(Q^2)$$



Available up to NLO  
 First NNLO calculations becoming available ...

# Jet properties measurement



## 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

“Measurement”



Jet

“Theory”

From measured energy to particle energy

Compensate energy loss due to neutrinos, nuclear excitation ...

From particle energy to original parton energy

Compensate hadronization; energy in/outside jet cone  
 ...

Needs Calibration

# Jet reconstruction

## Iterative cone algorithms:

Jet defined as energy flow within a cone of radius  $R$  in  $(y, \phi)$  or  $(\eta, \phi)$  space:

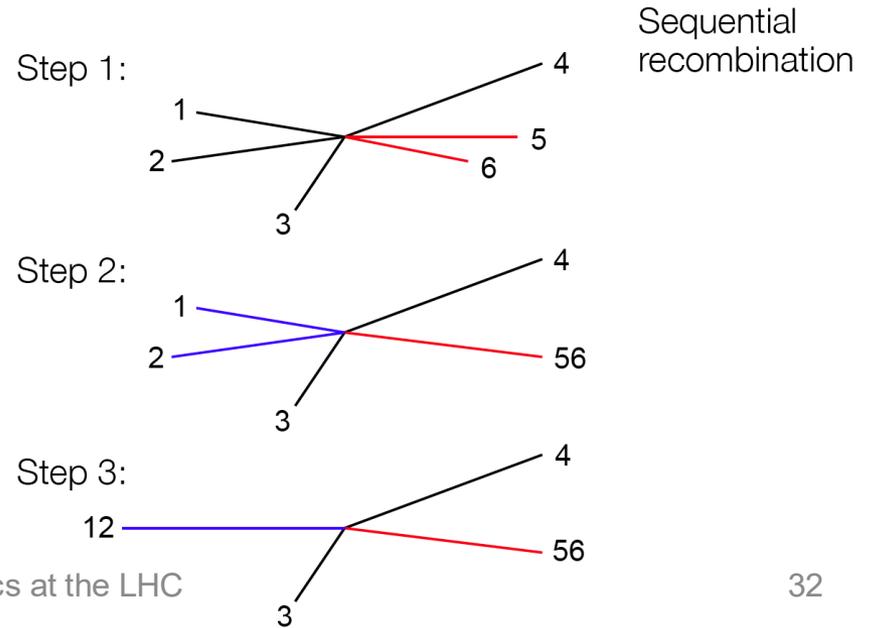
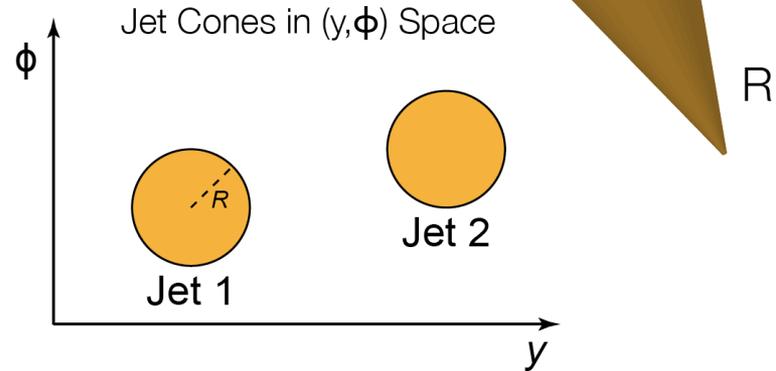
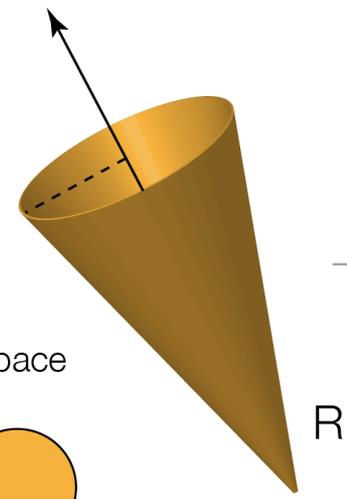
$$R = \sqrt{(y - y_0)^2 + (\phi - \phi_0)^2}$$

## Sequential recombination algorithms:

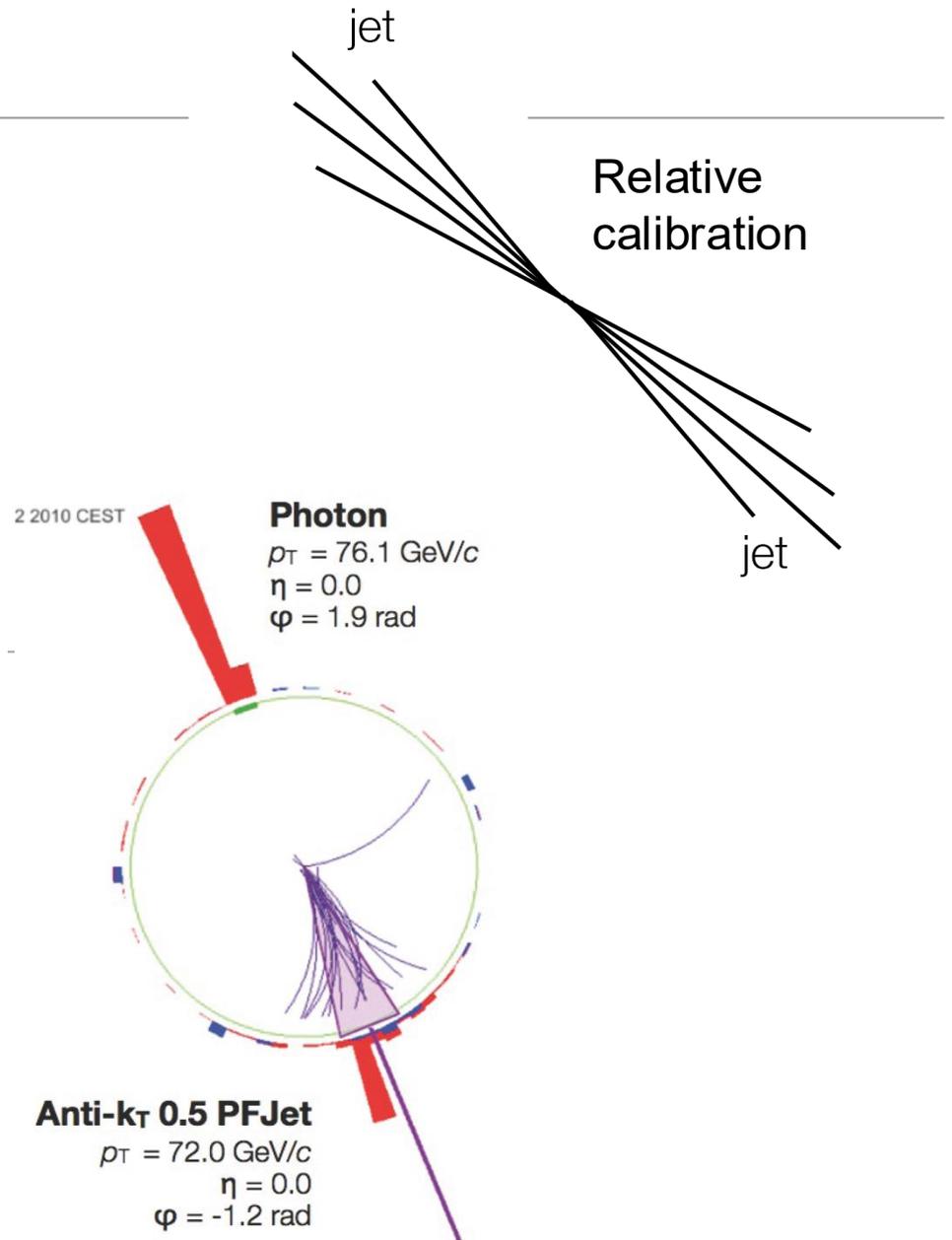
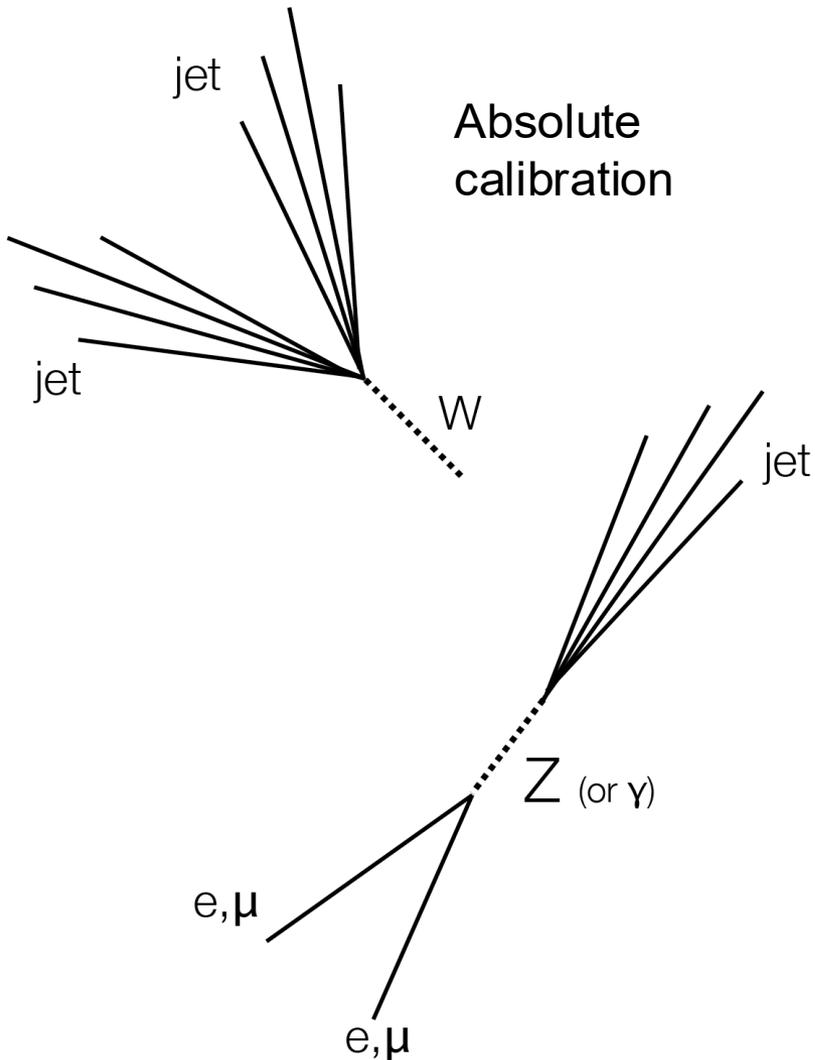
- Define distance measure  $d_{ij}$  ...
- Calculate  $d_{ij}$  for all pairs of objects ...
- Combine particles with minimum  $d_{ij}$  below cut ...
- Stop if minimum  $d_{ij}$  above cut ...

e.g.  $k_T$ -algorithm:  
[see later]

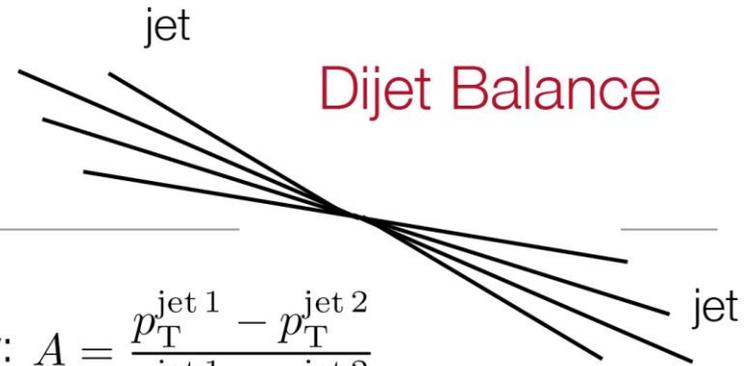
$$d_{ij} = \min(k_{T,i}^2, k_{T,j}^2) \frac{\Delta R_{ij}}{R}$$



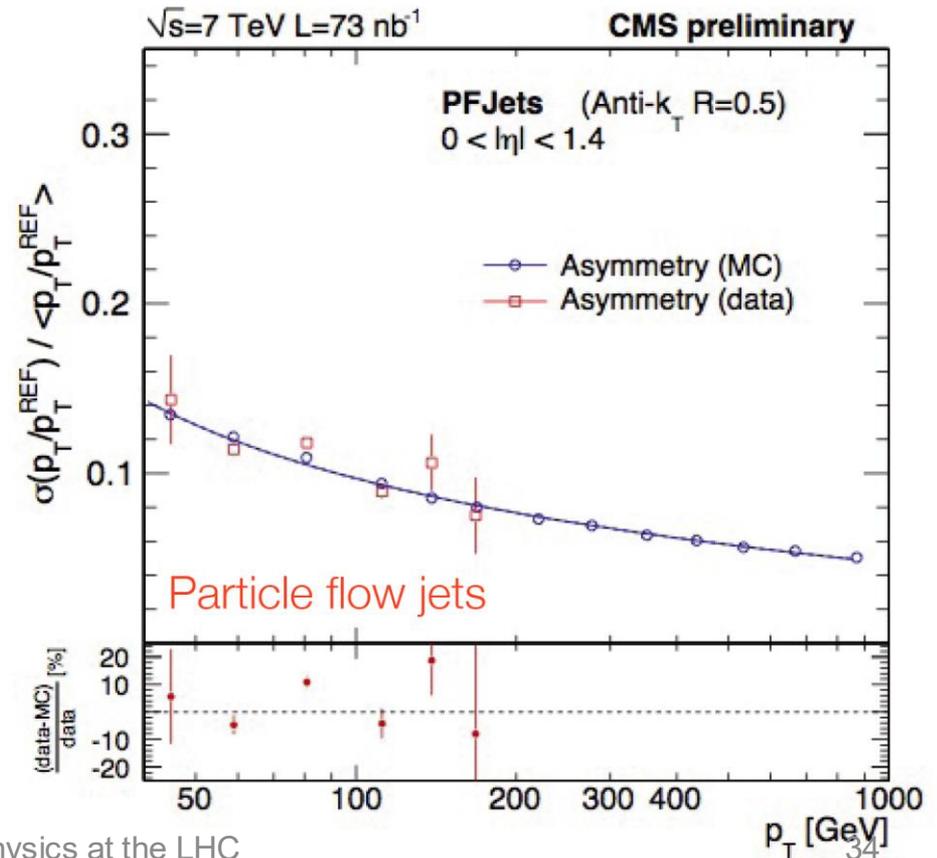
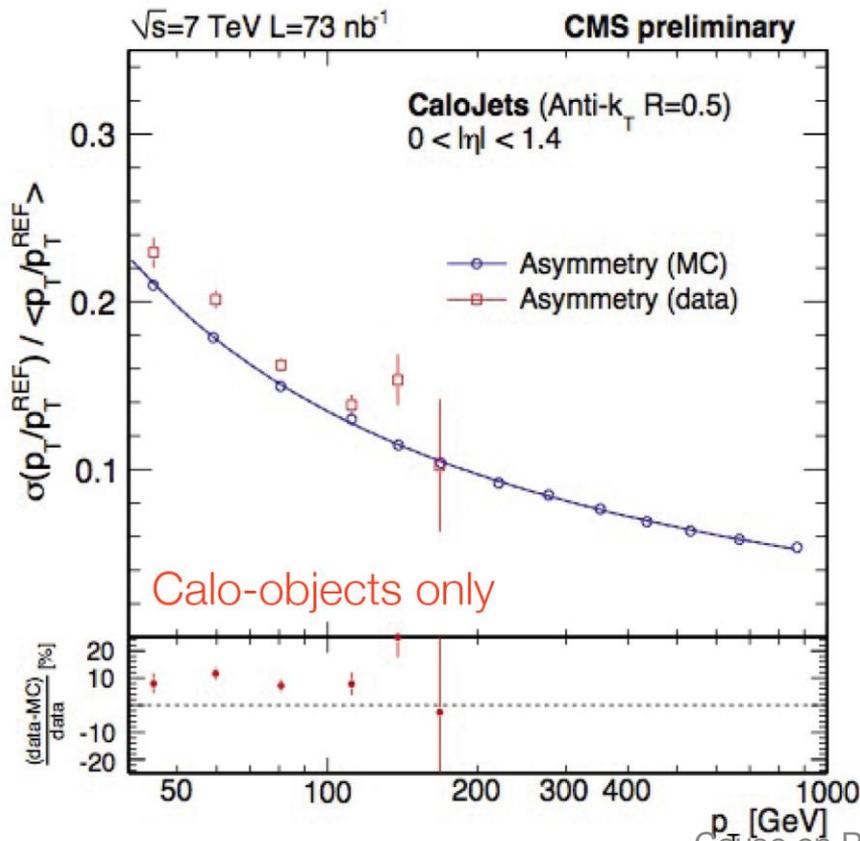
# Jet energy calibration



# Jet energy resolution



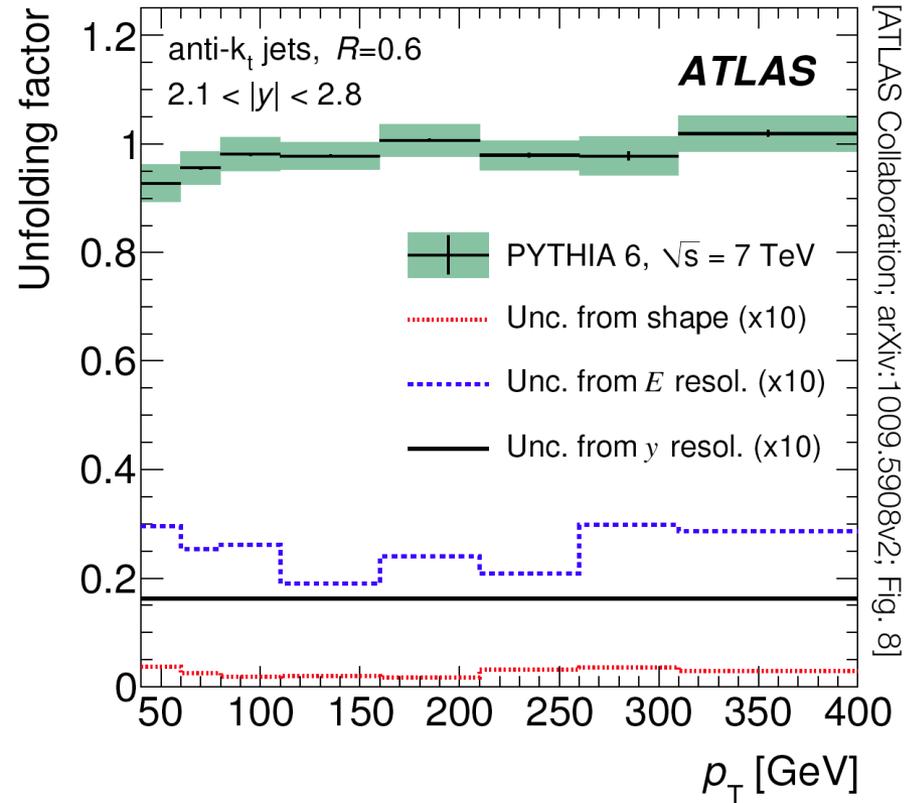
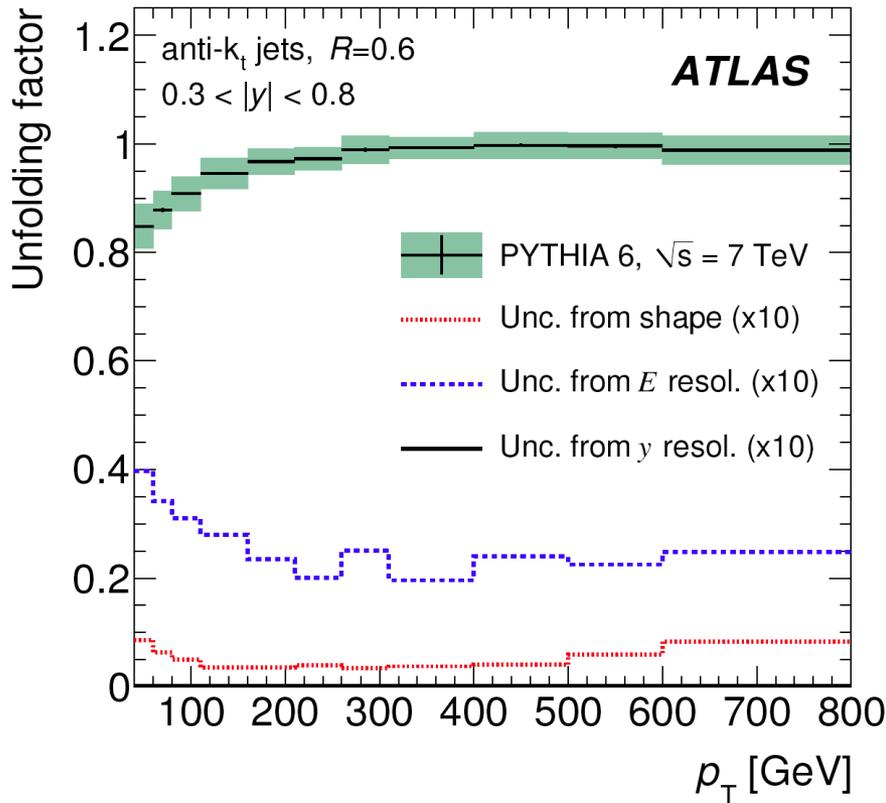
Resolution:  $\frac{\sigma(p_T)}{p_T} = \sqrt{2}\sigma_A$  using  $p_T$  asymmetry:  $A = \frac{p_T^{\text{jet } 1} - p_T^{\text{jet } 2}}{p_T^{\text{jet } 1} + p_T^{\text{jet } 2}}$



# Resolution unfolding

Measured spectrum =  
 Real spectrum  $\otimes$  Experim. resolution

$$N_{\text{part}} = N_{\text{meas}} \cdot \frac{N_{\text{part}}^{\text{MC}}}{N_{\text{meas}}^{\text{MC}}}$$



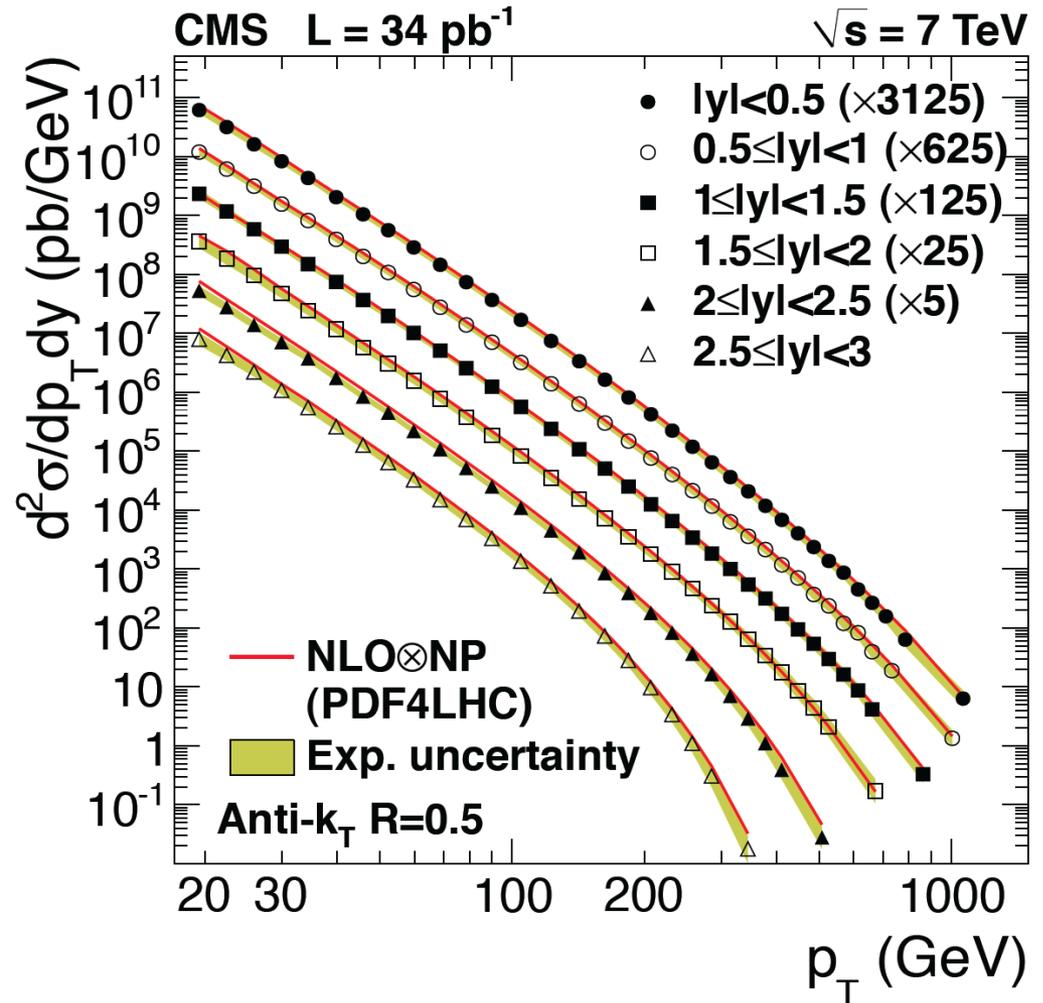
# Inclusive jet cross-section

Cross section is huge  
(~ Tevatron x 100)

Very good agreement with  
NLO QCD over nine orders of  
magnitude

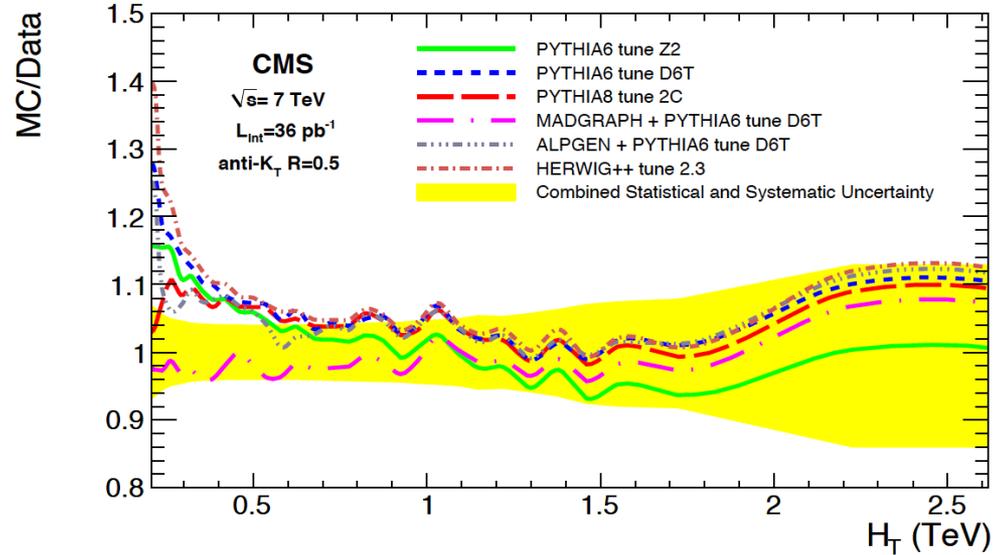
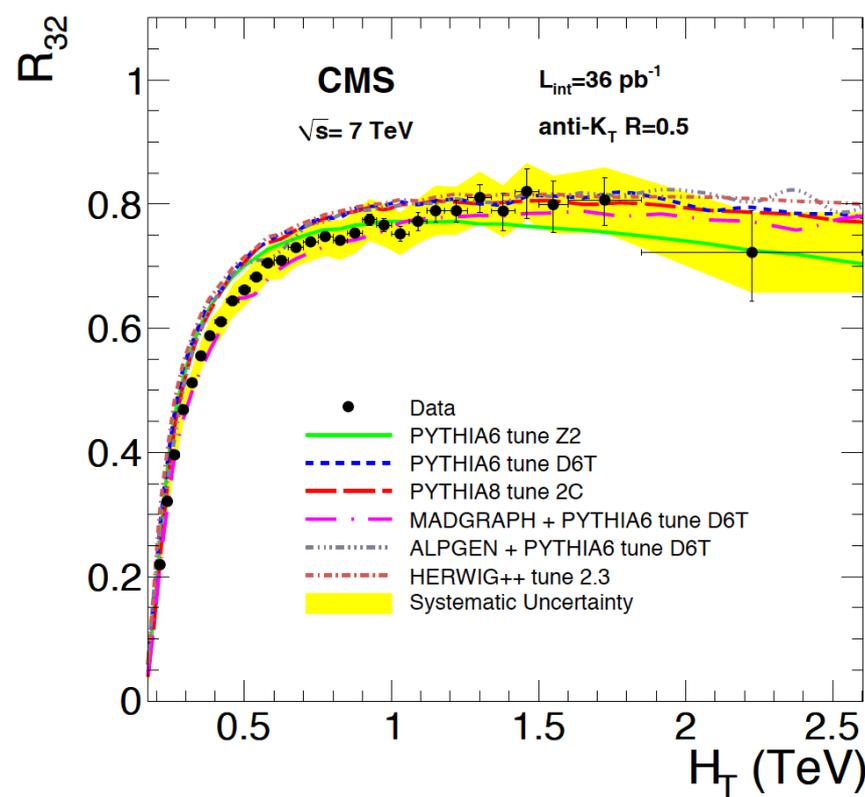
PT extending from 20 to 500  
GeV

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



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

hep-ex 1106.0647, PLB 702 (2011) 336



$$H_T = \sum_{i=1}^N p_{T_i}$$

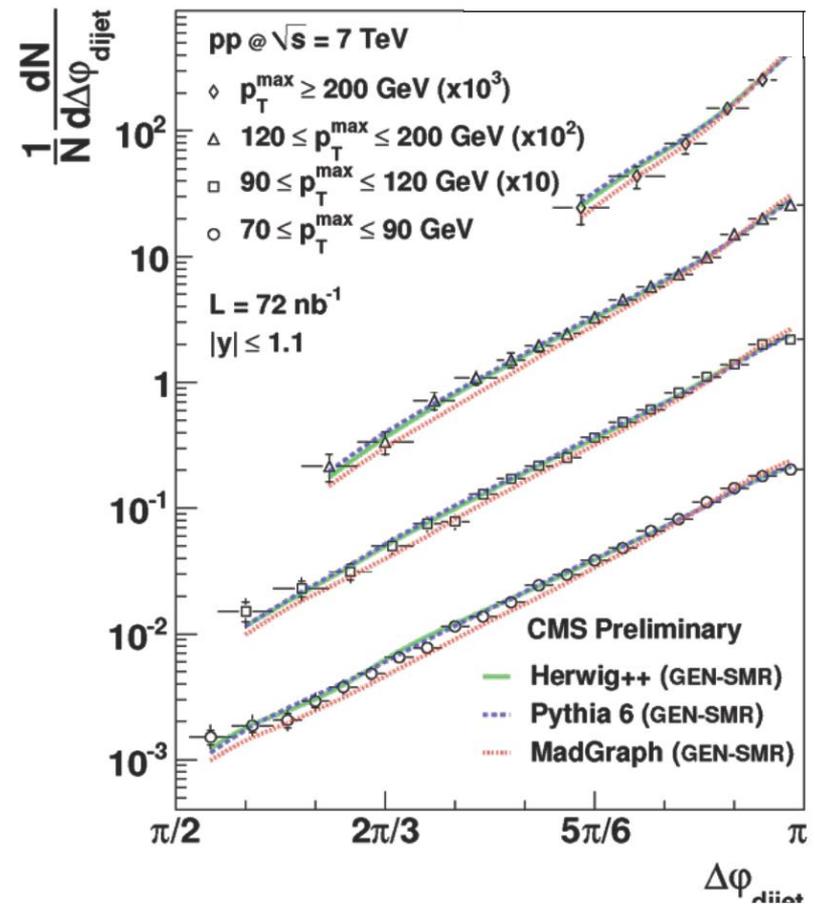
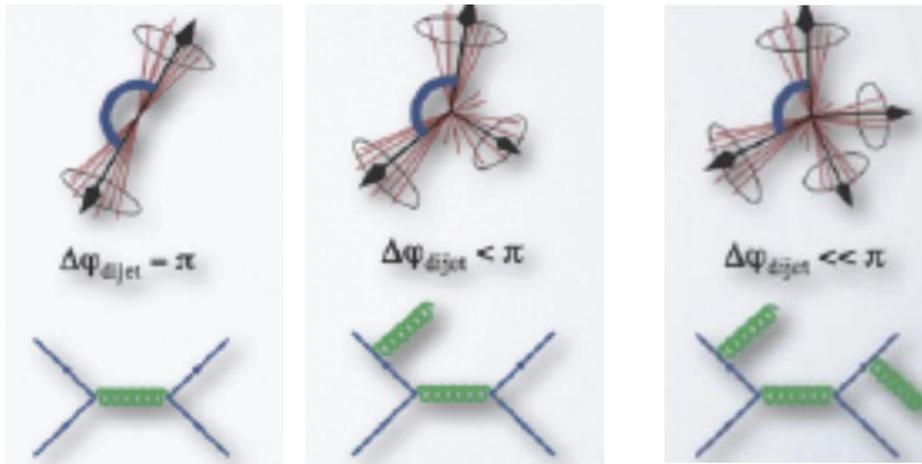
# Jets: angular correlations

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

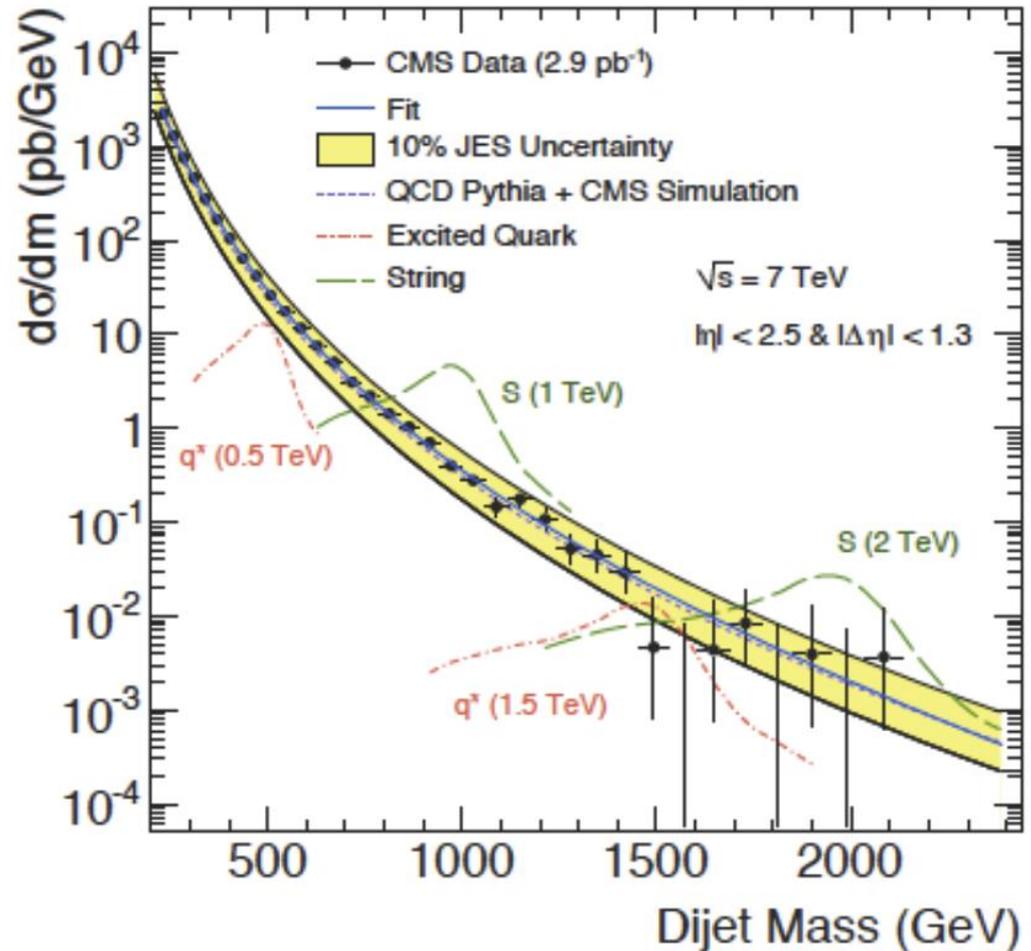
BSM:

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

Four-parameter fit to describe  
QCD shape:

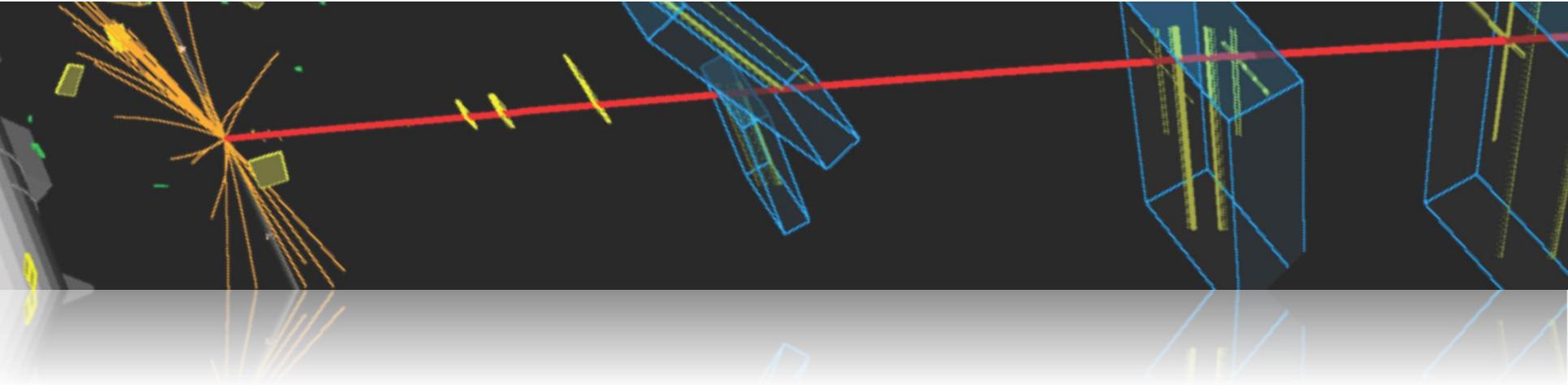
$$\frac{d\sigma}{dm} = p_0 \frac{\left(1 - \frac{m}{\sqrt{s}}\right)^{p_1}}{\left(\frac{m}{\sqrt{s}}\right)^B};$$

$$B = p_2 + p_3 \left(m/\sqrt{s}\right)$$



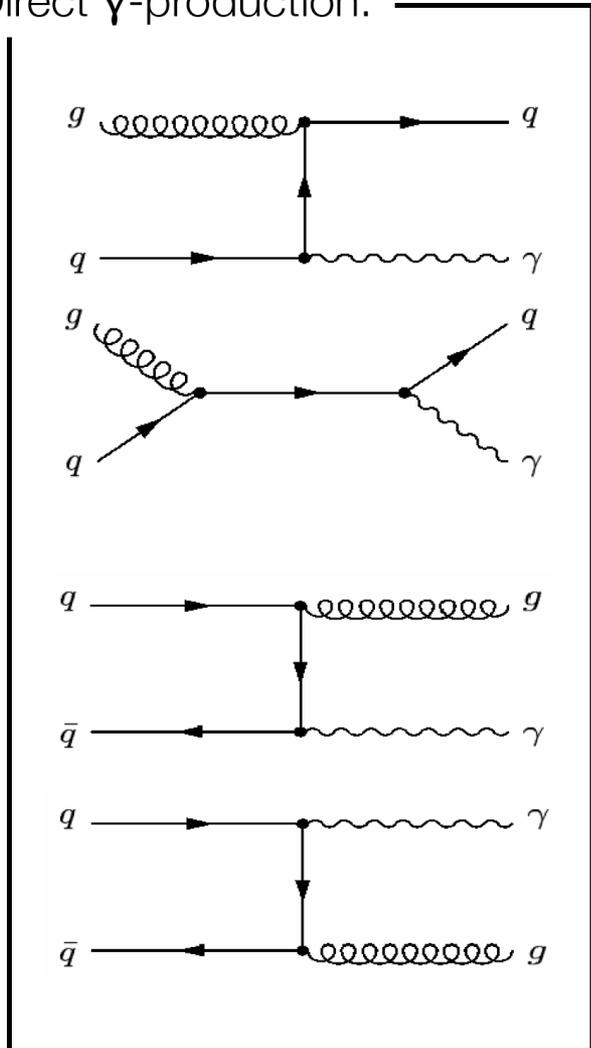
# End of Lecture 2

# W and Z bosons

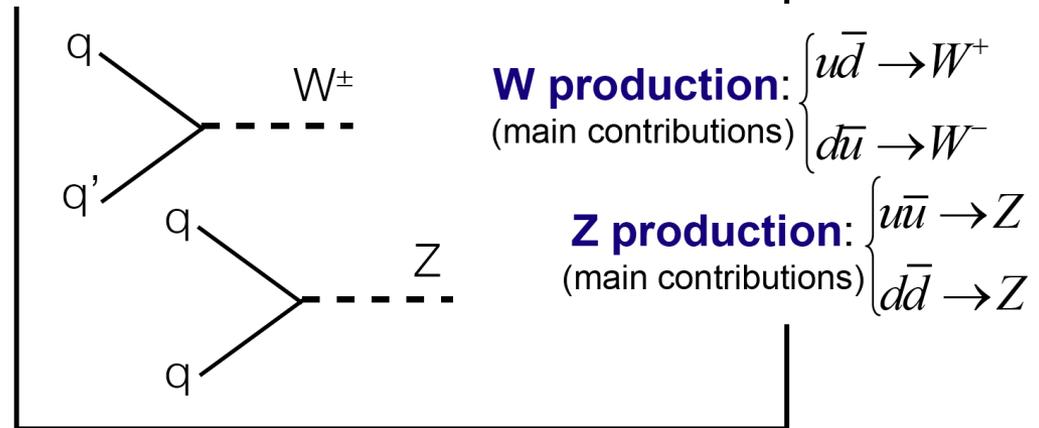


# Vector boson production

Direct  $\gamma$ -production:



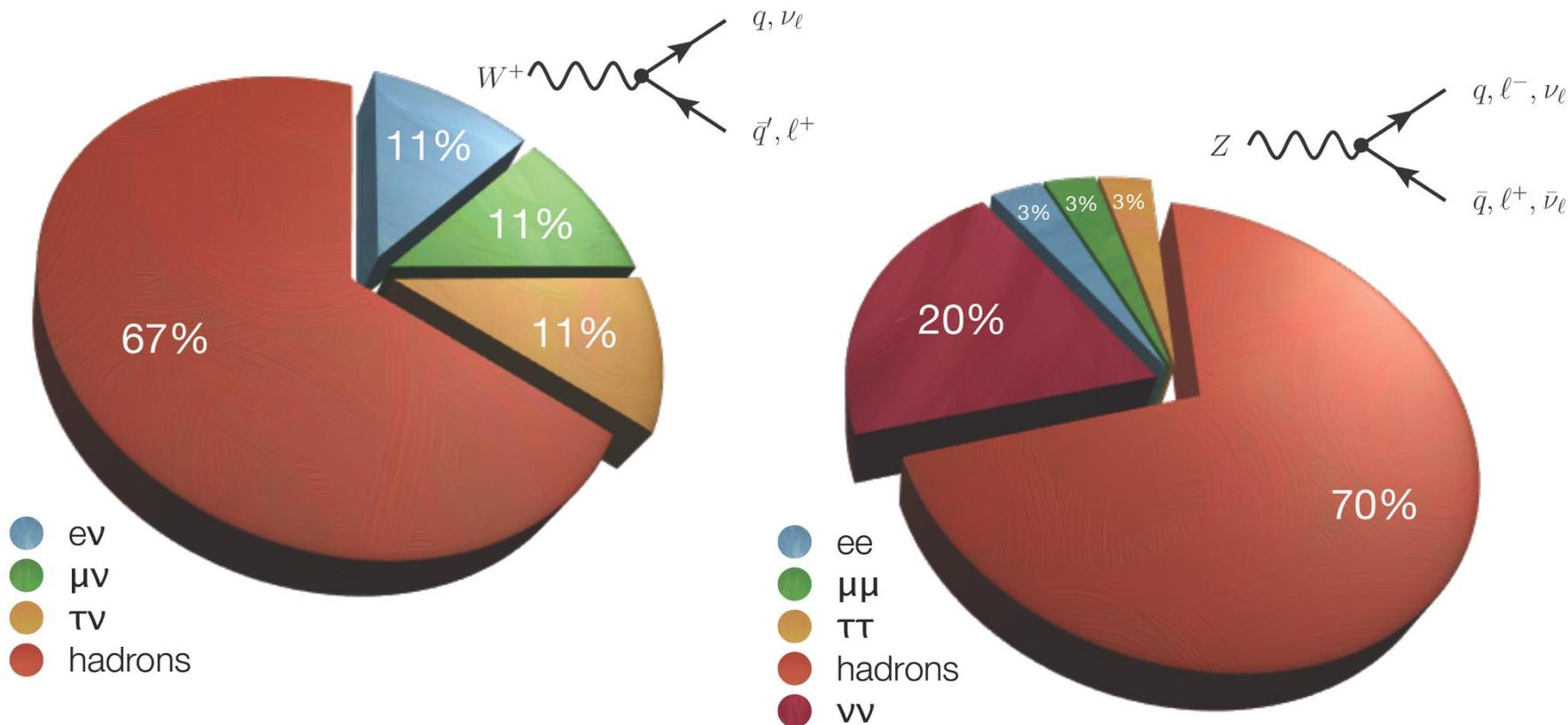
Singlet W/Z production:



- 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/ $\mu$ ): very clean, but small(ish) branching fractions

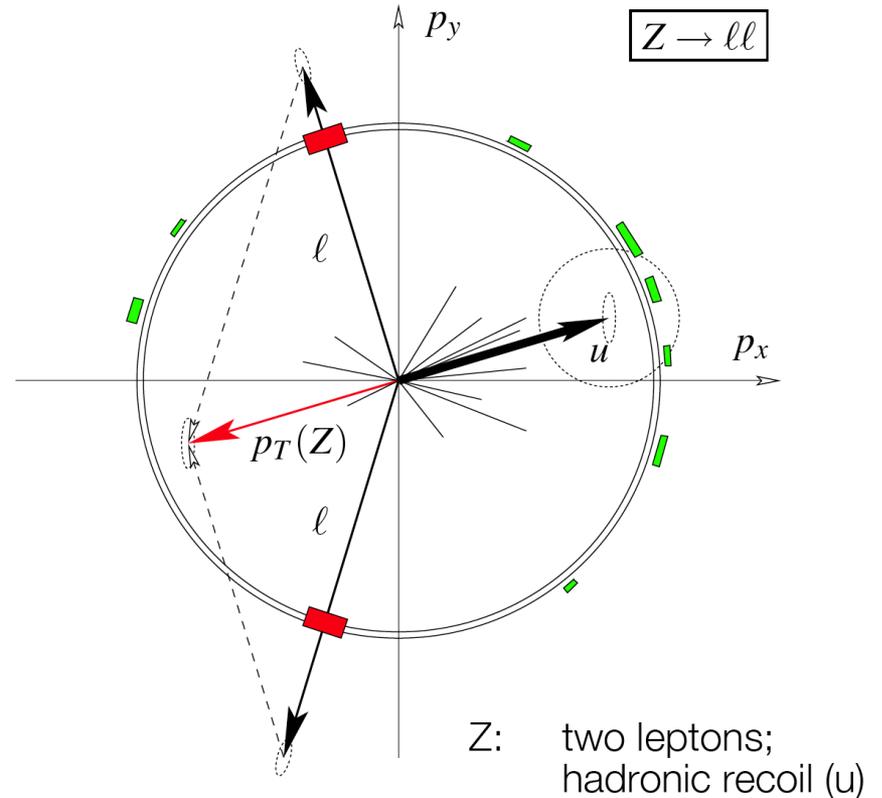
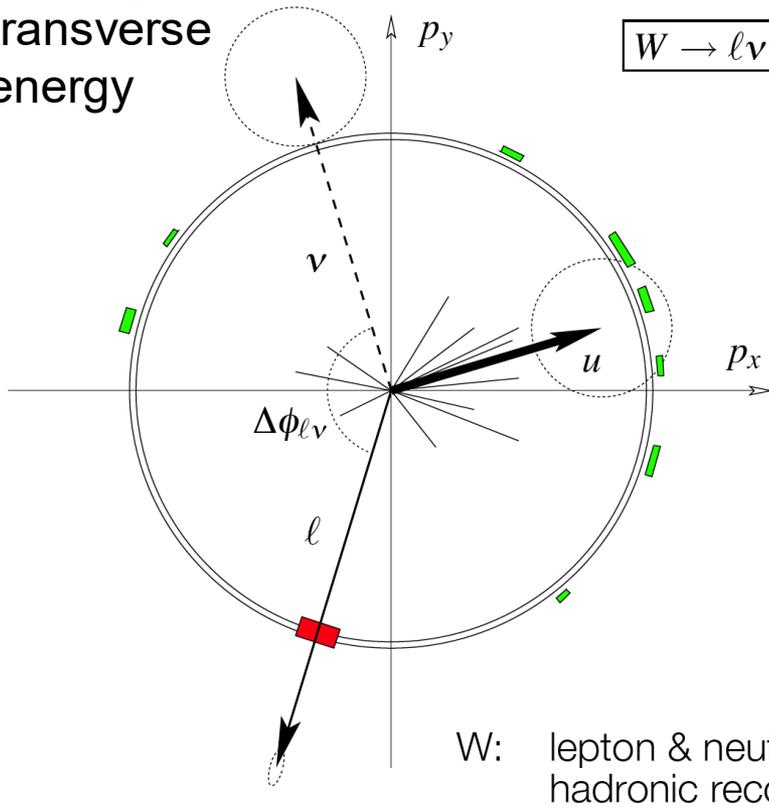
Hadronic decays: two-jet final states; large QCD dijet background

Tau decays: somewhere in between...

# W and Z boson signatures

[CERN-OPEN-2008-020]

Missing  
transverse  
energy



Additional hadronic activity  $\rightarrow$  recoil, not as clean as  $e^+e^-$   
Precision measurements: only leptonic decays

# Isolated High- $p_T$ Leptons

Starting point for many hadron collider analyses:

**isolated high- $p_T$  leptons**  $\rightarrow$  discriminate against QCD jets ...

QCD jets can be **mis-reconstructed** as leptons (“fake leptons”)

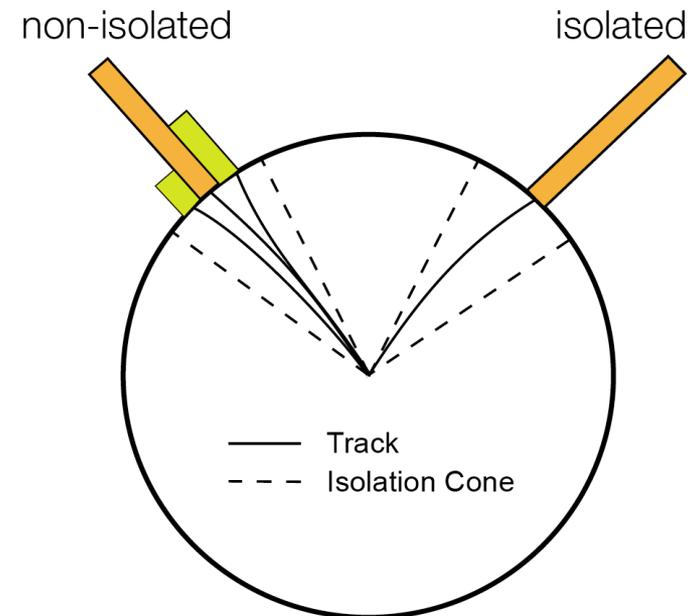
QCD jets may contain **real leptons**  
e.g. from semileptonic B decays [ $B \rightarrow l\nu_X$ ]

$\rightarrow$  soft and surrounded by other particles

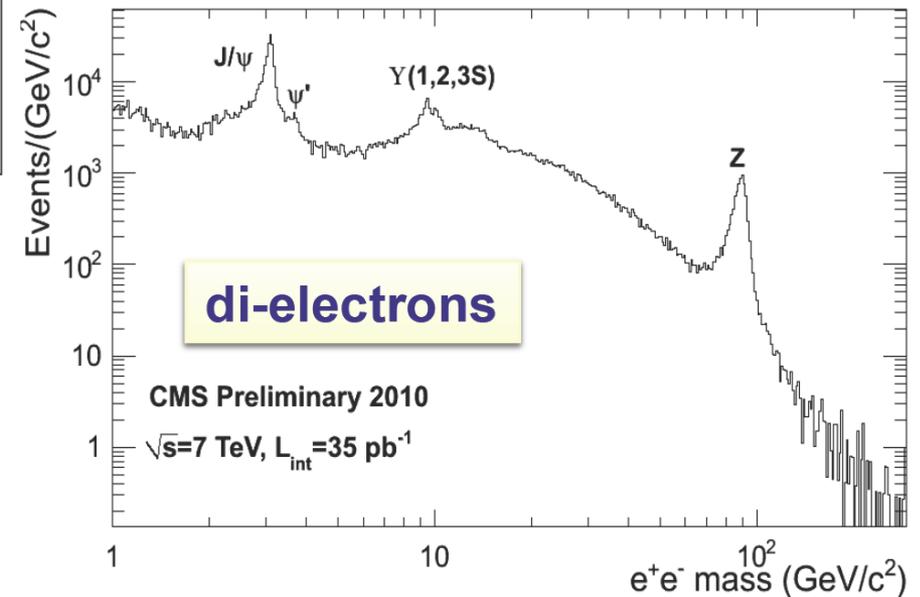
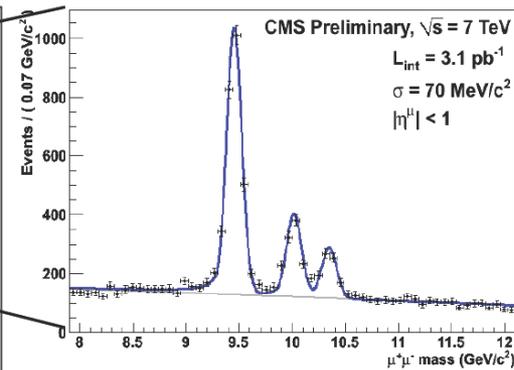
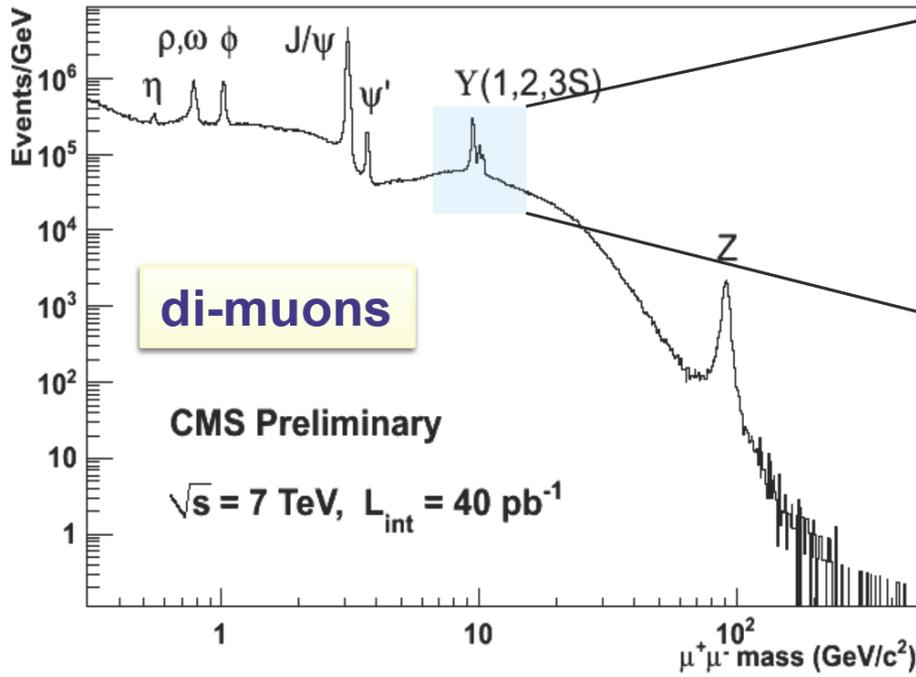
“Tight” lepton selection ...

Require  $e/\mu$  with  $p_T >$  (at least) 20 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  $\Delta R=0.2$  less than 10%



# Dilepton mass spectrum at 7 TeV



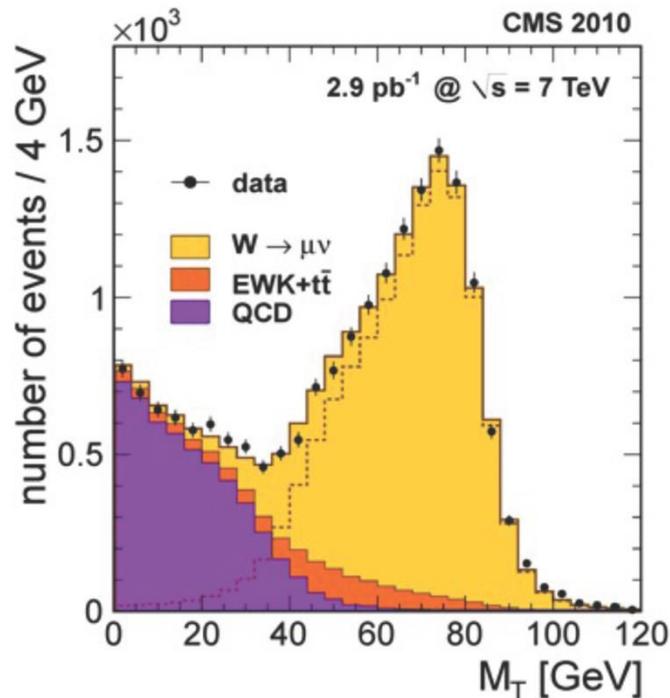
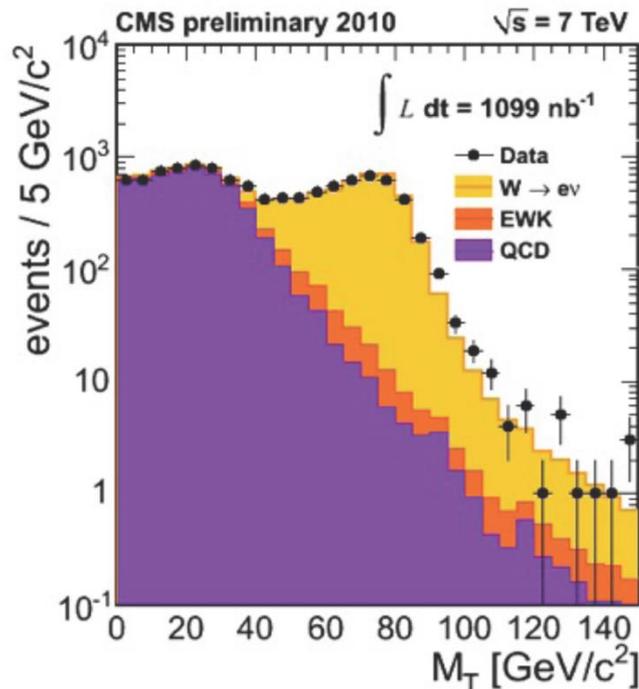
# Example: CMS W Analysis

Select isolated electrons and muons ...

[muons:  $p_T > 9$  GeV; electrons:  $p_T > 20$  GeV]

Investigate transverse mass ...

[Use  $E_{T,miss}$ ;  $M_T = (p_{lep} + E_{T,miss})^{1/2}$ ]

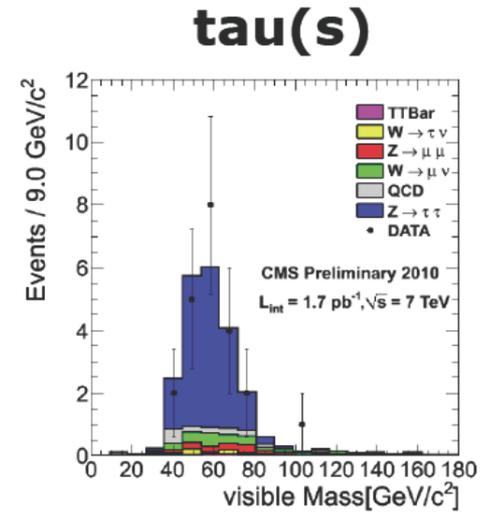
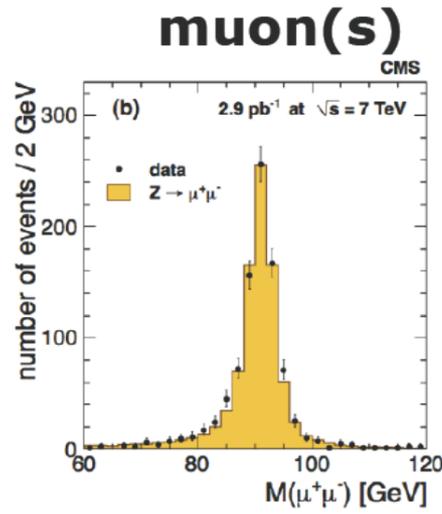
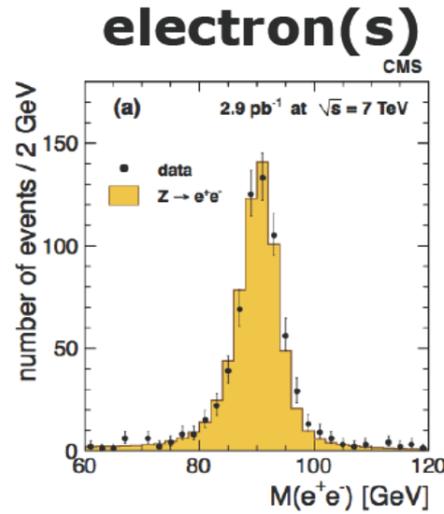


The W signal yield is extracted from a binned likelihood fit to the  $M_T$  distribution. Three different contributions:

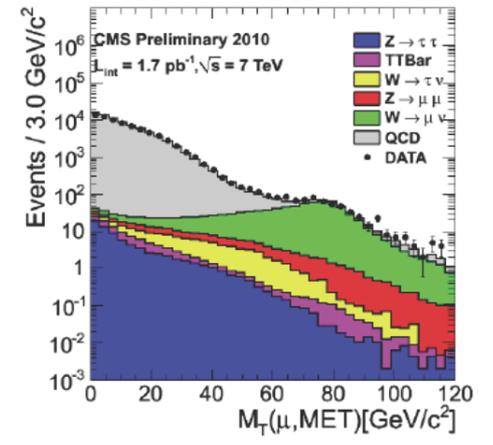
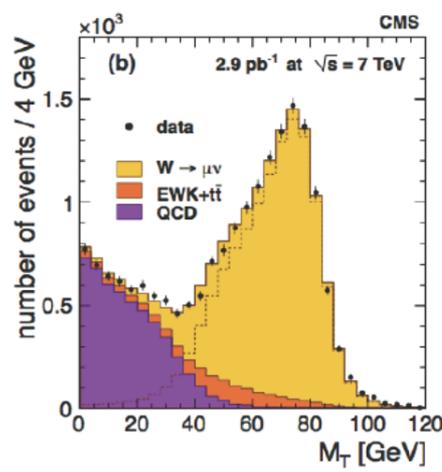
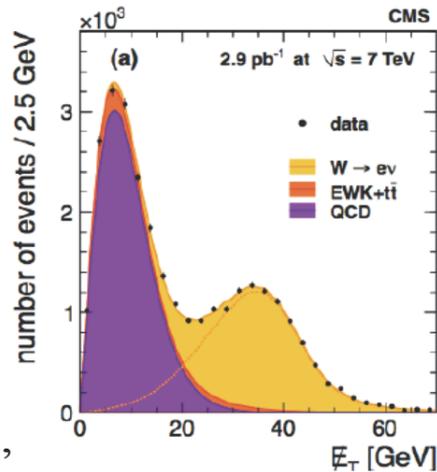
- W signal
- QCD background
- other (EWK) backgrounds.

# W/Z production at 7 TeV

**Z BOSON**



**W BOSON**

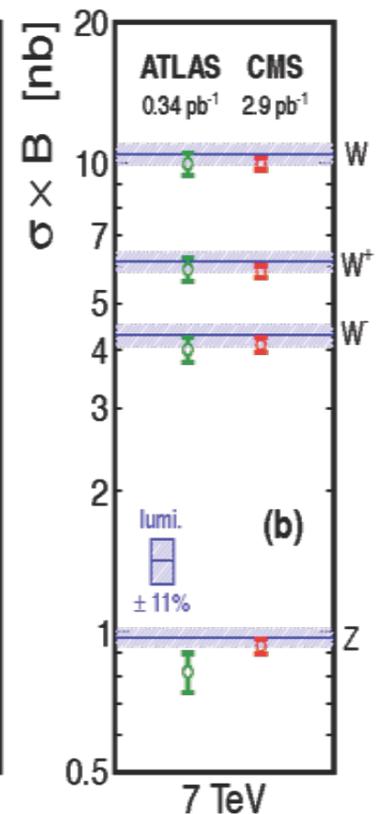
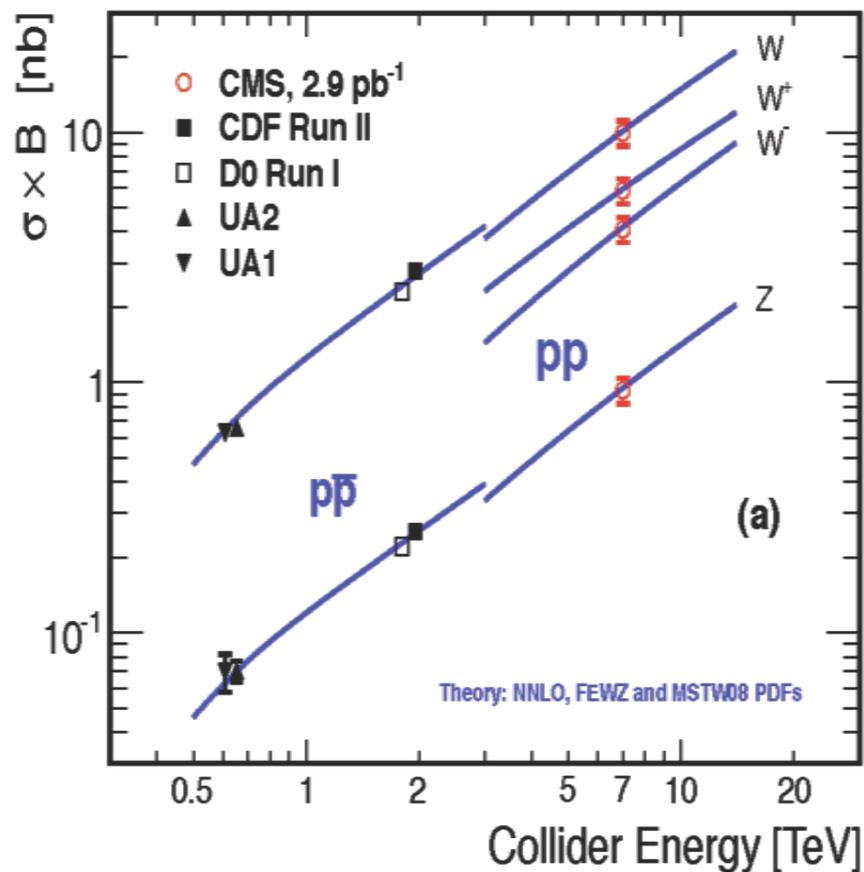
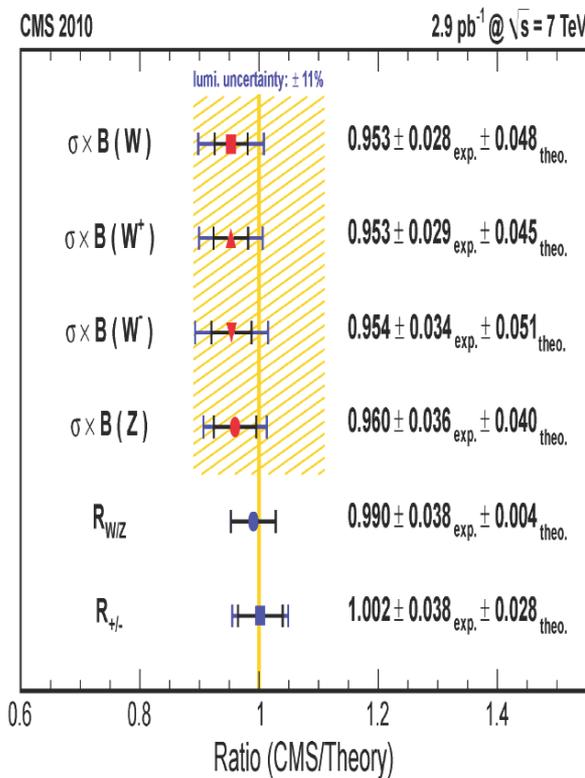


Transverse Mass,

$$M_T = \sqrt{2E_T^\mu E_T^{\text{miss}} (1 - \cos \Delta\phi_{e, \text{miss}})}$$

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

hep-ex 1012.2466, JHEP 01 (2011) 080



# W<sup>+</sup>/W<sup>-</sup> charge asymmetry

NNLO cross sections:  
scale uncertainties very small

W rapidity: **asymmetry**  
[sensitivity to PDFs]

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

Proton-Proton Collider:

**symmetry** around  $y=0$  ...

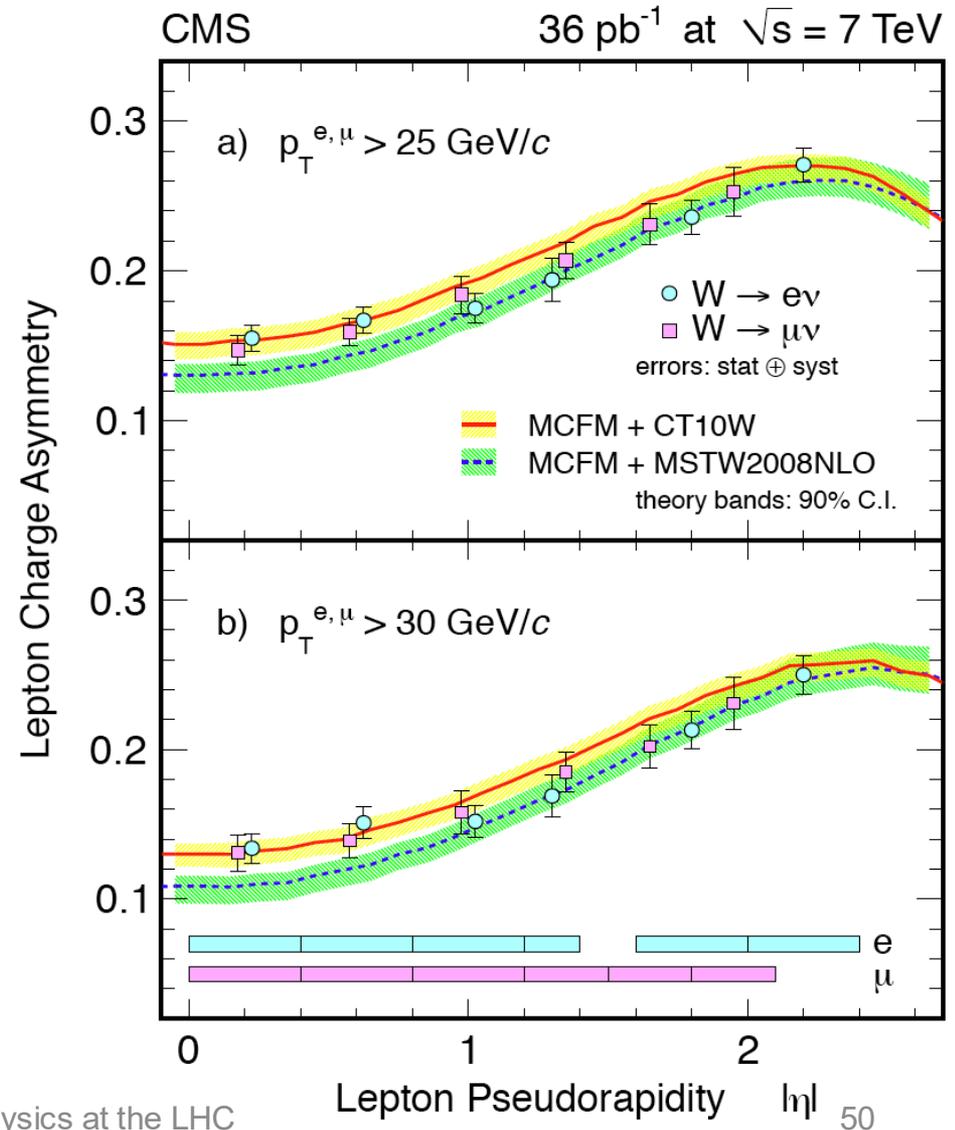
PDFs:

$u(x) > d(x)$  for large  $x$  ...

**more W<sup>+</sup> at positive rapidity**

$d/u$  ratio  $< 1$  ...

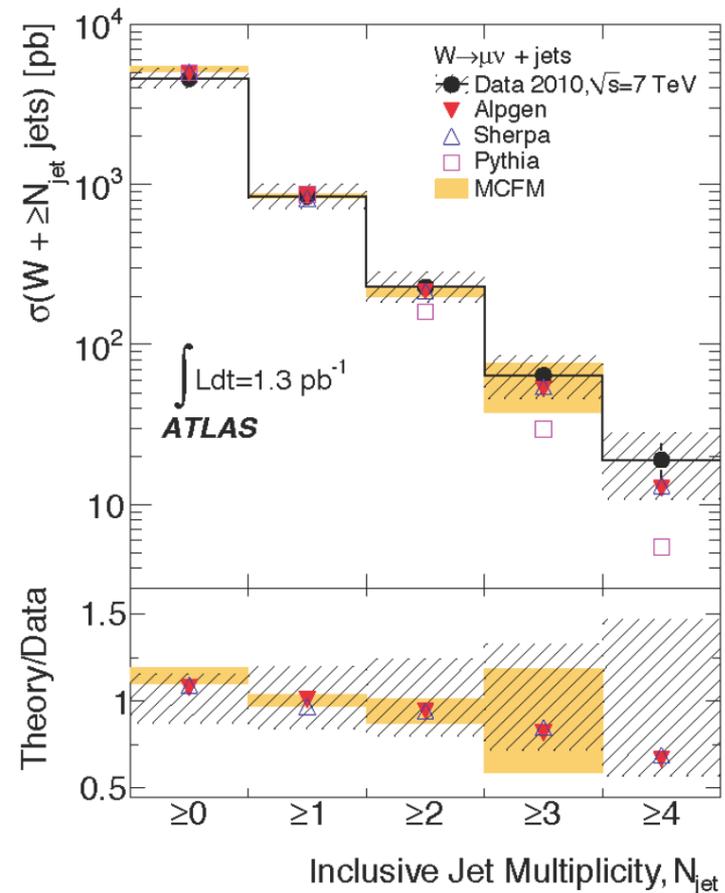
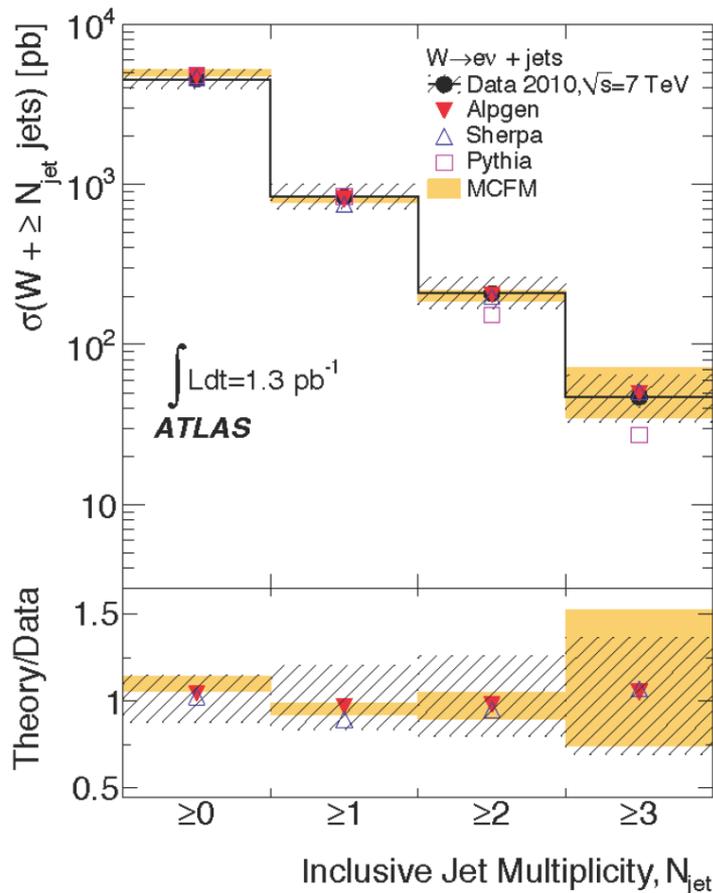
**always more W<sup>+</sup> than W<sup>-</sup>**



# W + Jets multiplicity

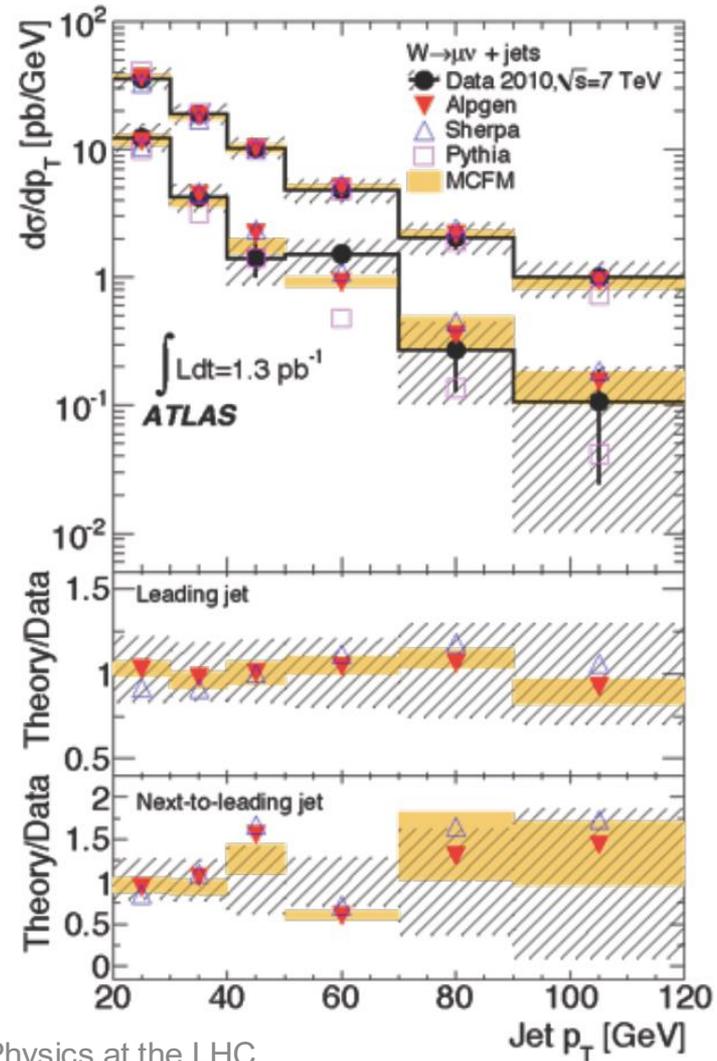
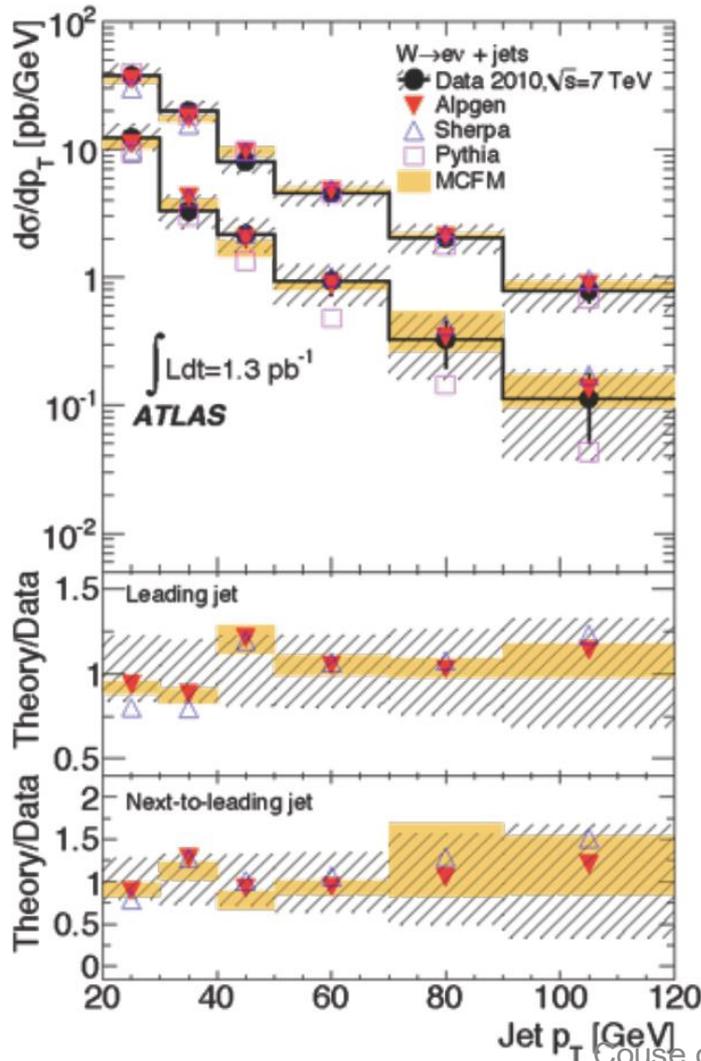
$|\eta| < 2.8$  and  $p_T > 20$  GeV

arXiv:1012.5382

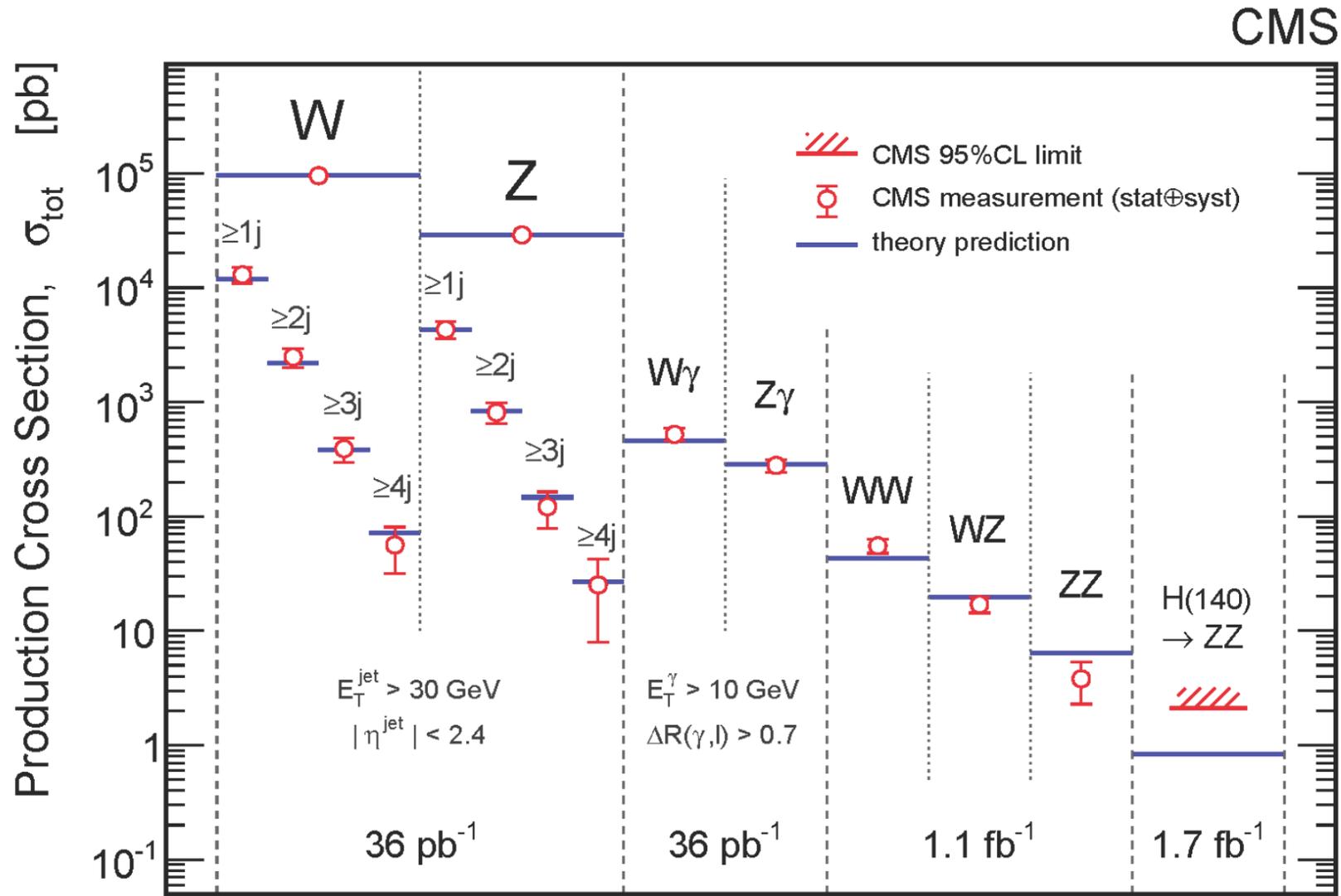


# W + Jets $P_T$

Tails are important in several Exotica and SUSY searches



# SM processes measured at LHC



# W Mass Determination

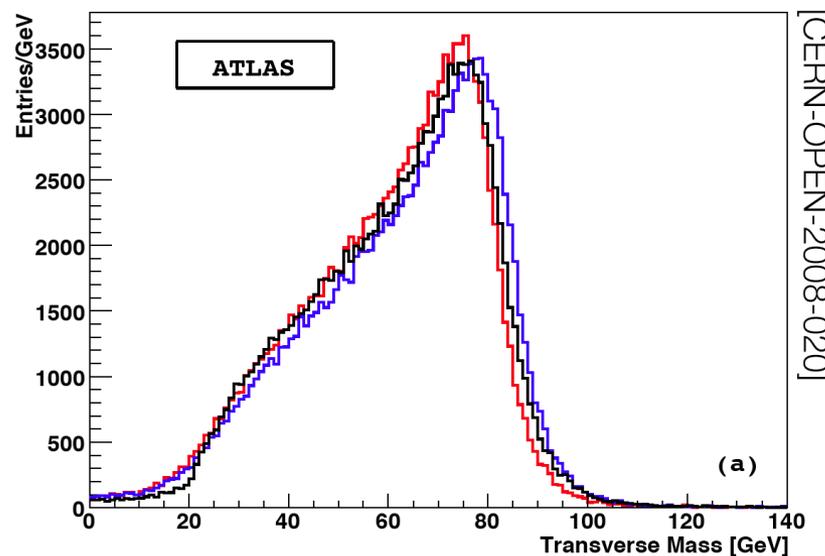
## Template method:

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]