



Course on Physics at the LHC

Lecture 2

Introduction to collisions at LHC

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Lisbon, PORTUGAL
MARCH – MAY 2024

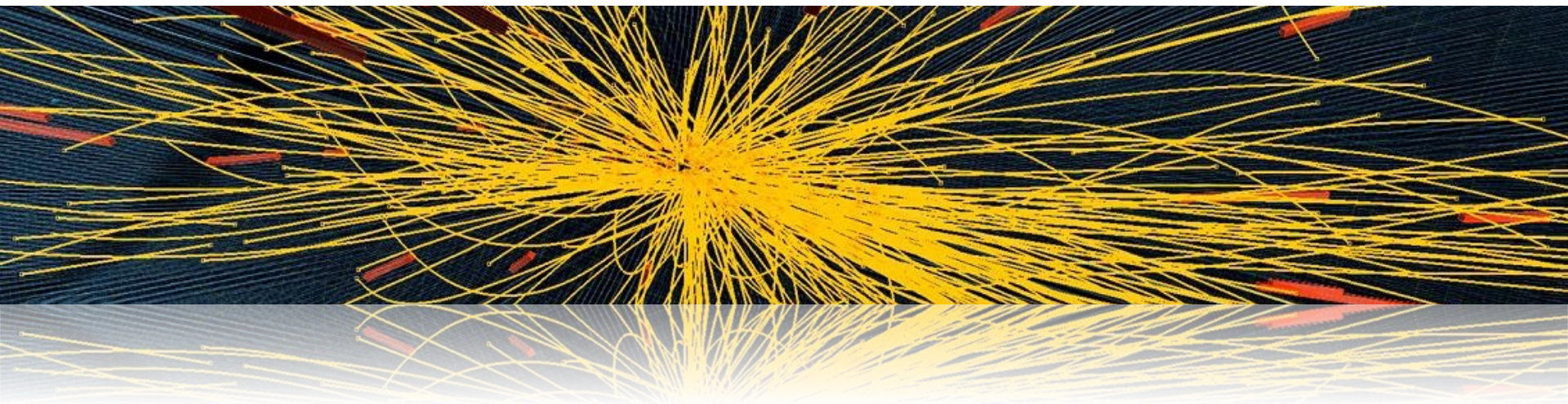


LABORATÓRIO DE INSTRUMENTAÇÃO
E FÍSICA EXPERIMENTAL DE PARTÍCULAS
partículas e tecnologia

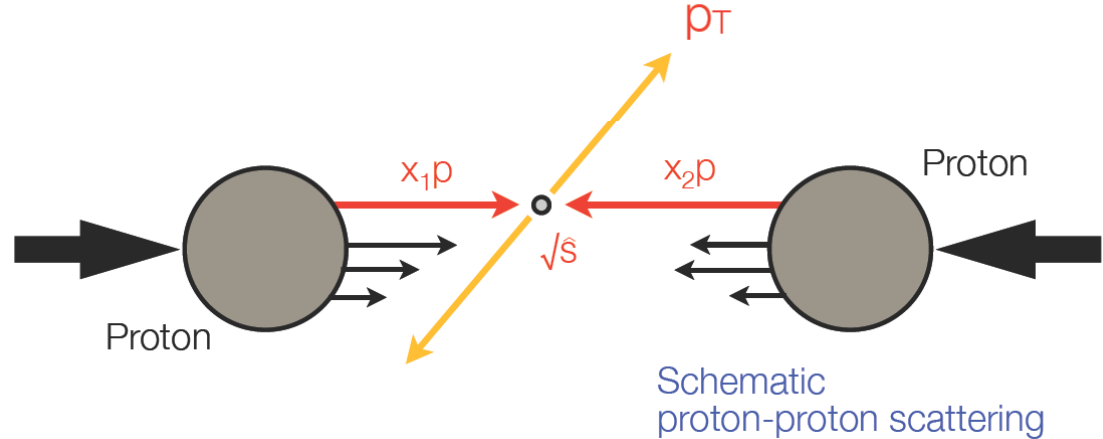
Introduction to collisions at LHC

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

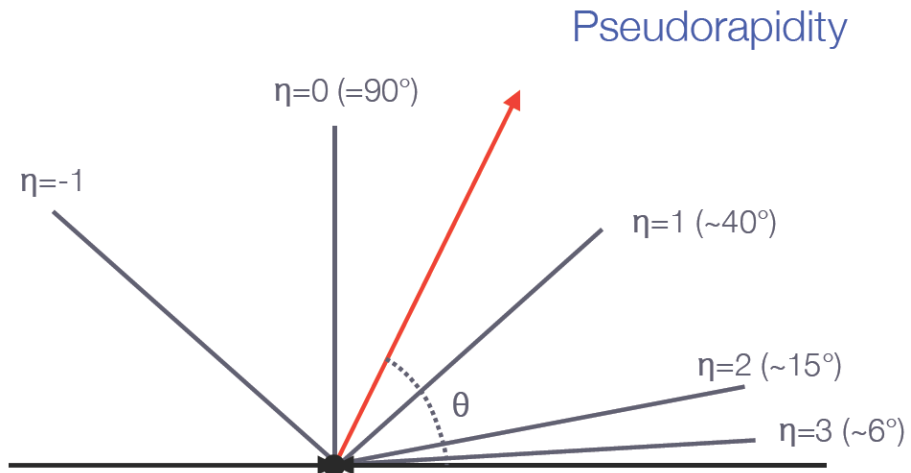


Kinematical variables

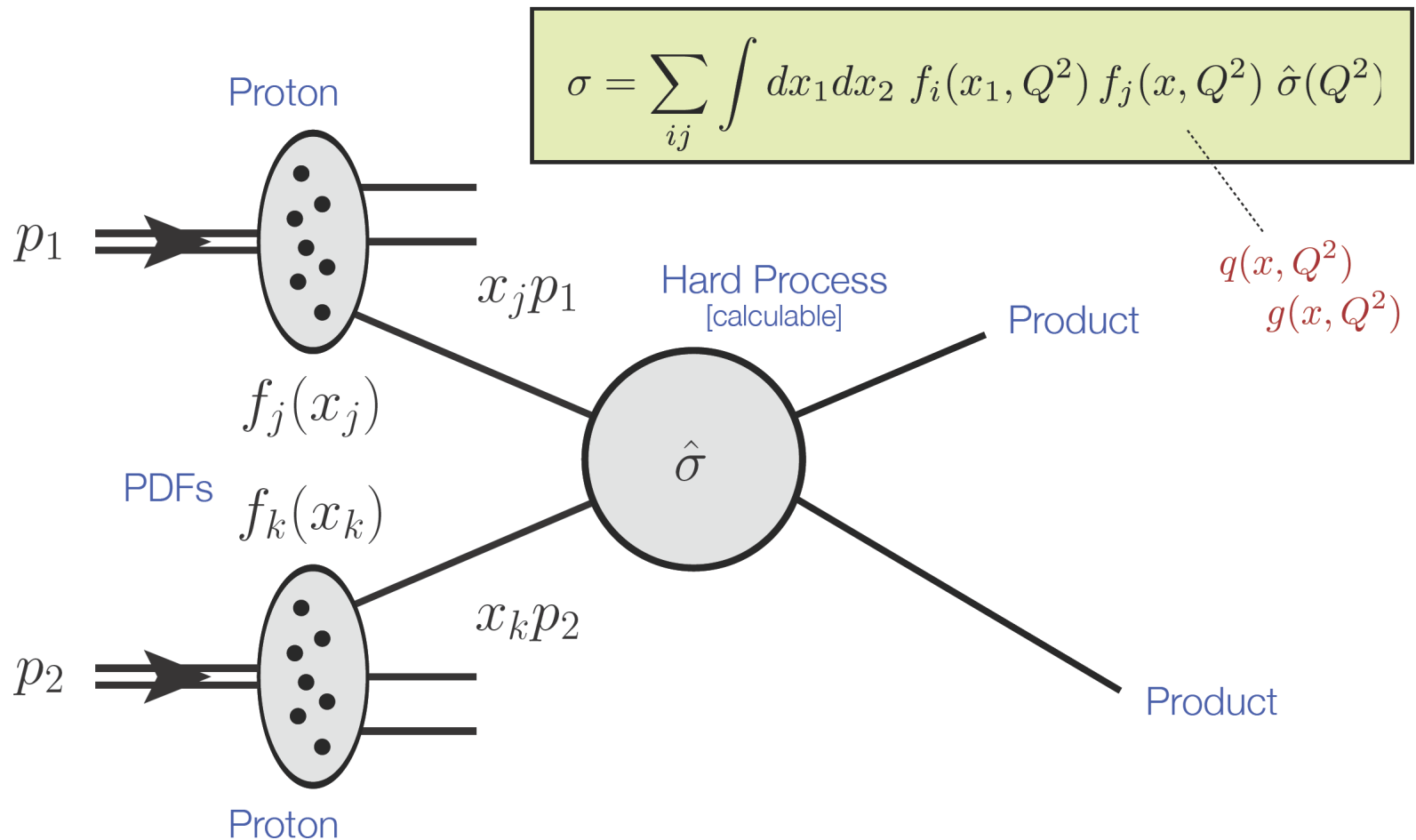


Relevant kinematic variables:

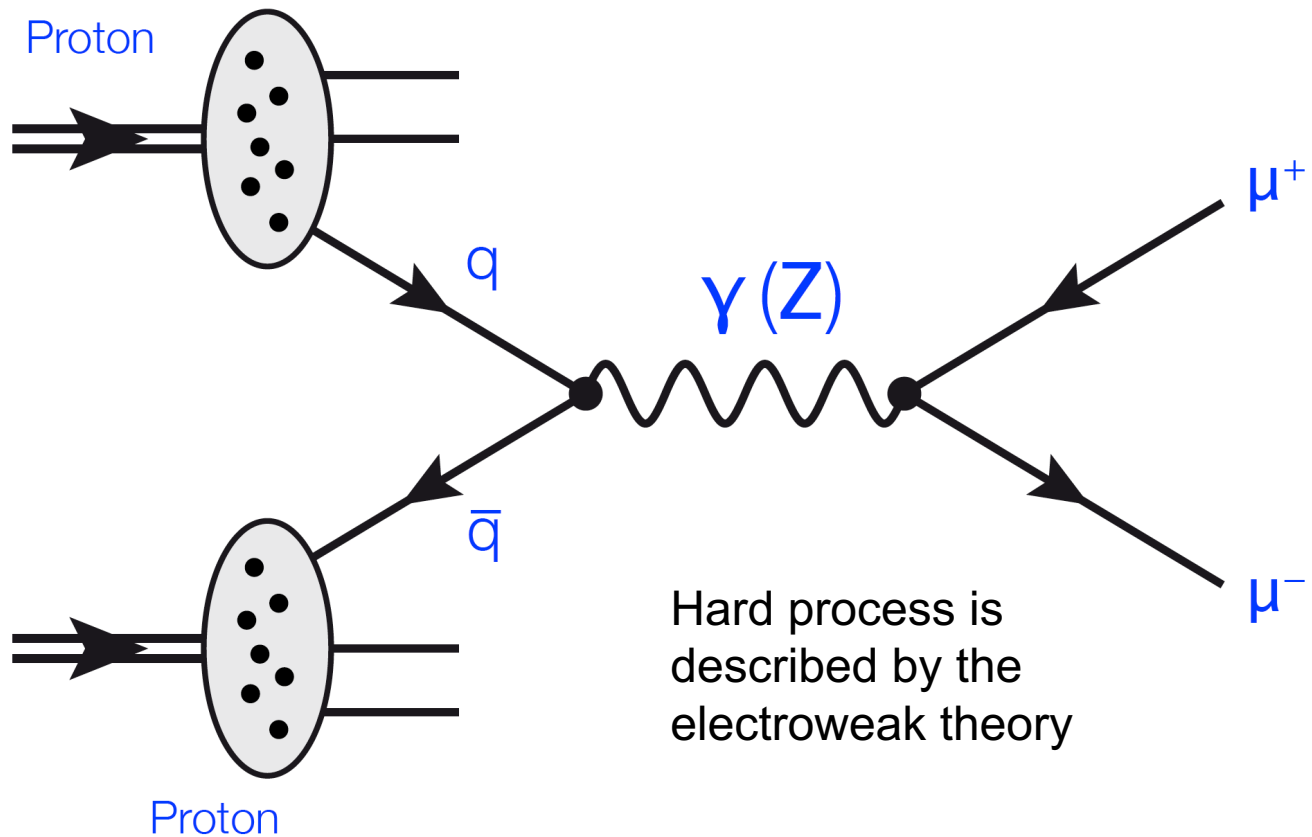
- Transverse momentum: p_T
- Rapidity: $y = \frac{1}{2} \cdot \ln (E-p_z)/(E+p_z)$
- Pseudorapidity: $\eta = -\ln \tan \frac{1}{2}\theta$
- Azimuthal angle: φ



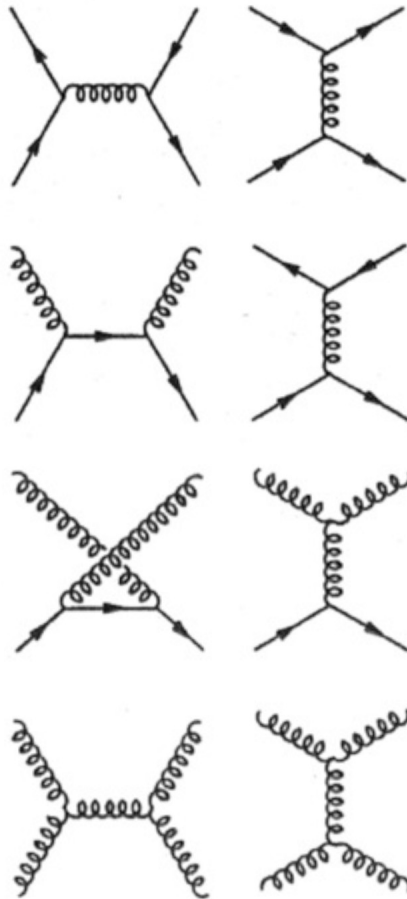
Proton-Proton Scattering



Example: Drell-Yan Process

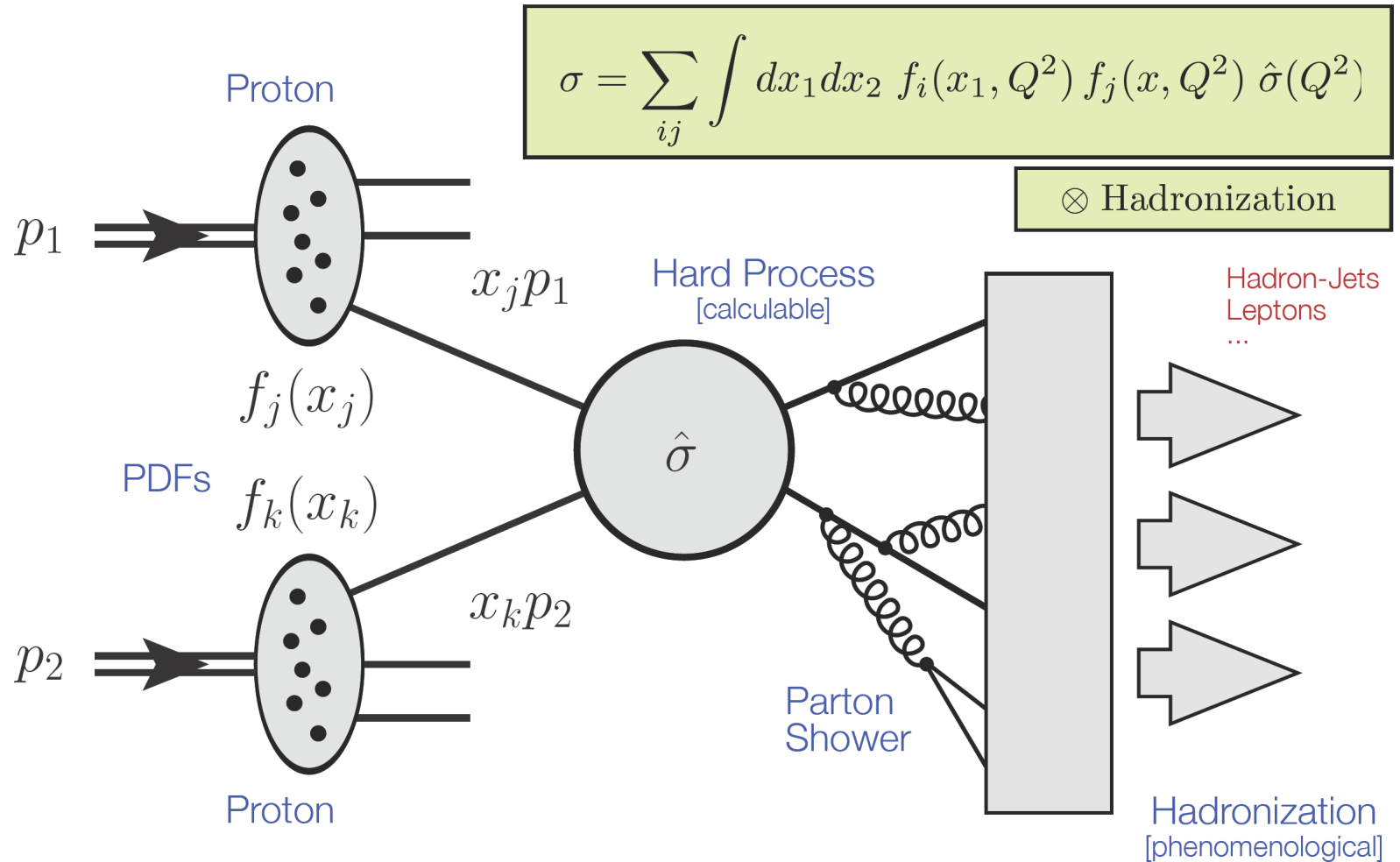


QCD processes



Subprocess	$ \mathcal{M} ^2/g_s^4$	$ \mathcal{M}(90^\circ) ^2/g_s^4$
$qq' \rightarrow qq'$ $q\bar{q}' \rightarrow q\bar{q}'$	$\frac{4}{9} \frac{\hat{s}^2 + \hat{u}^2}{\hat{t}^2}$	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

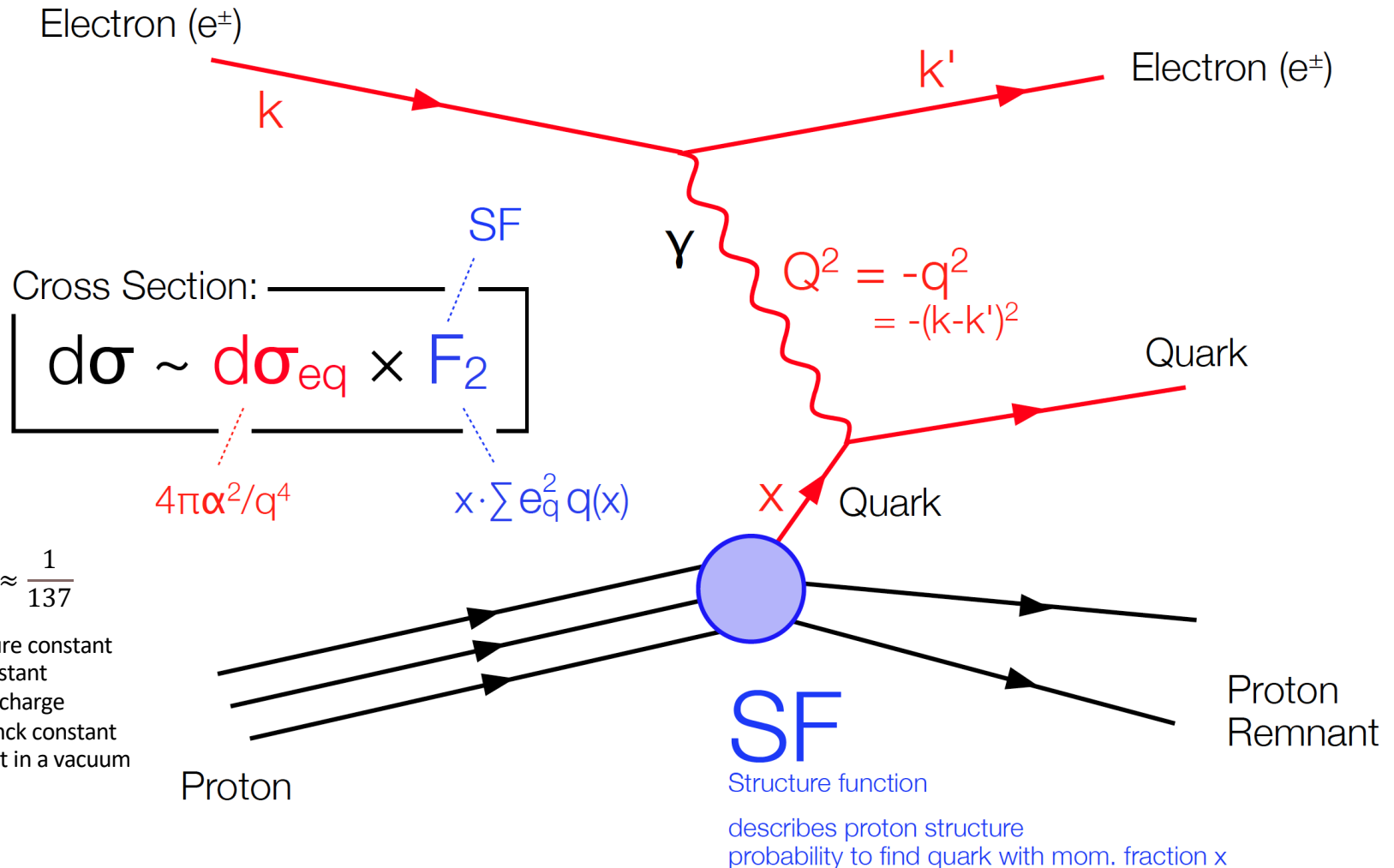
Proton-Proton Scattering: final state



QCD & parton densities



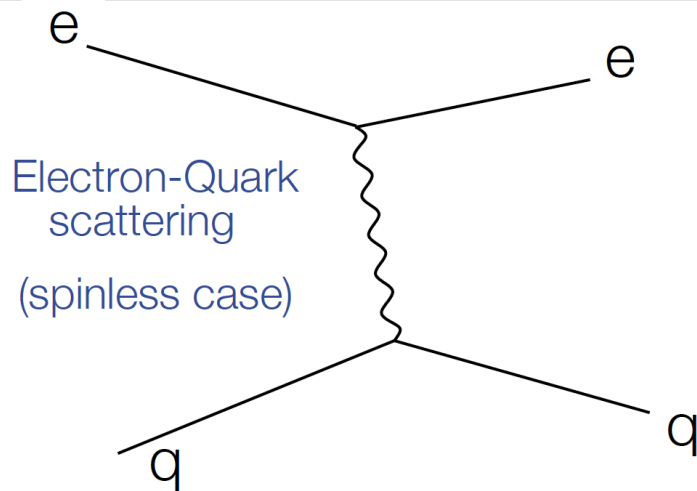
Lepton-proton scattering and proton structure



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

α = Fine-structure constant
 ϵ_0 = electric constant
 e = elementary charge
 \hbar = reduced Planck constant
 c = speed of light in a vacuum

Structure Function

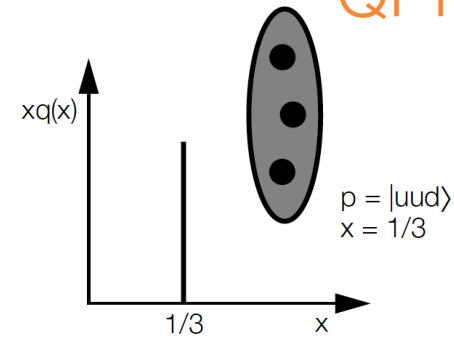


$$\frac{d\sigma(eq)}{dq^2} = \frac{4\pi\alpha^2}{q^4} e_q^2$$

Rutherford scattering
on pointlike target

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

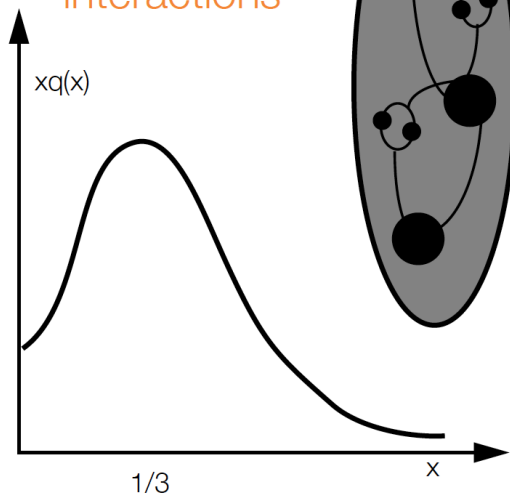
Naive
QPM



$$e_u = 2/3$$

$$e_d = -1/3$$

With
quark-quark
interactions



$$\begin{aligned} \frac{d\sigma(ep)}{dx dq^2} &= \frac{4\pi\alpha^2}{q^4} [e_u^2 u(x) + e_d^2 d(x) + \dots] \\ &= \frac{4\pi\alpha^2}{q^4} \frac{F_2(x)}{x} \end{aligned}$$

QPM: Structure Functions F_2 independent of Q^2

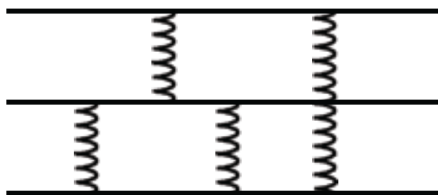
Proton

Three
valence quarks



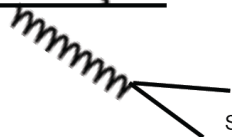
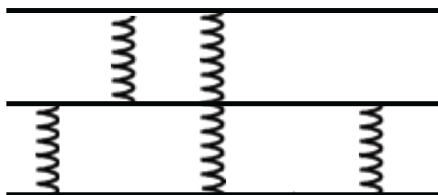
Proton

Three bound
valence quarks



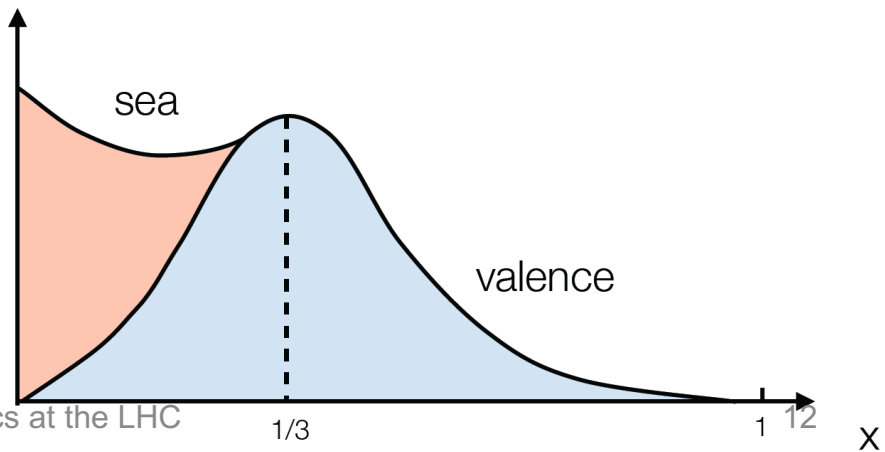
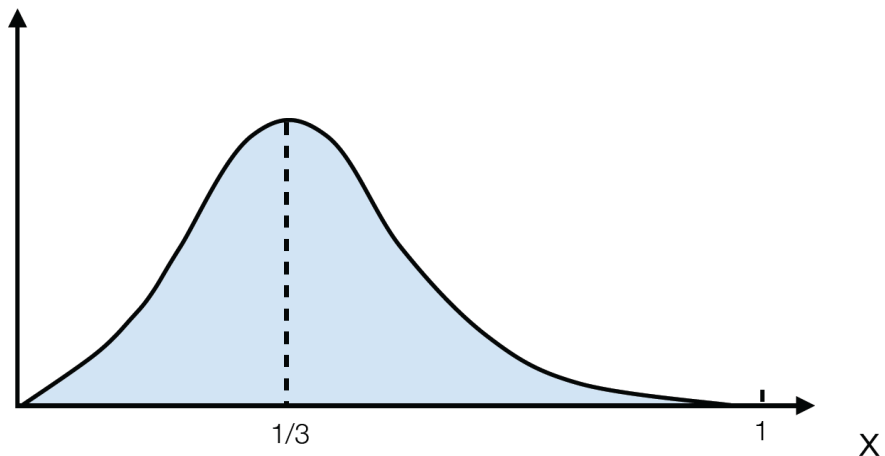
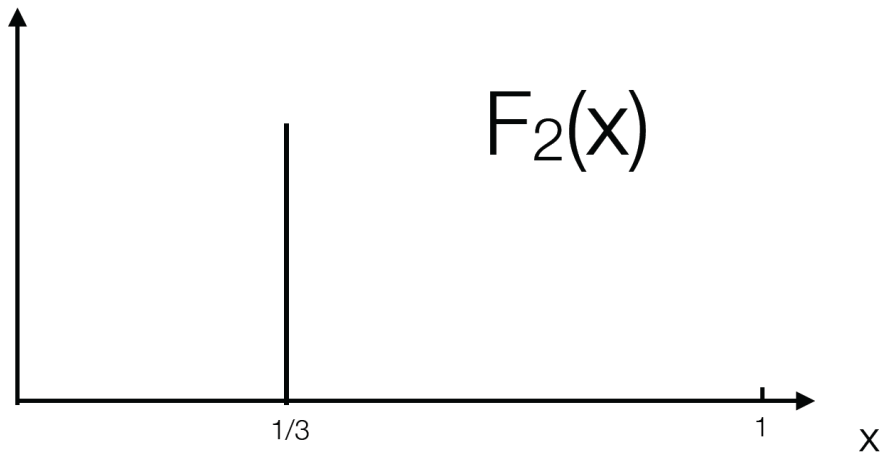
Proton

Bound valence
quarks + gluon radiation



small x

$F_2(x)$



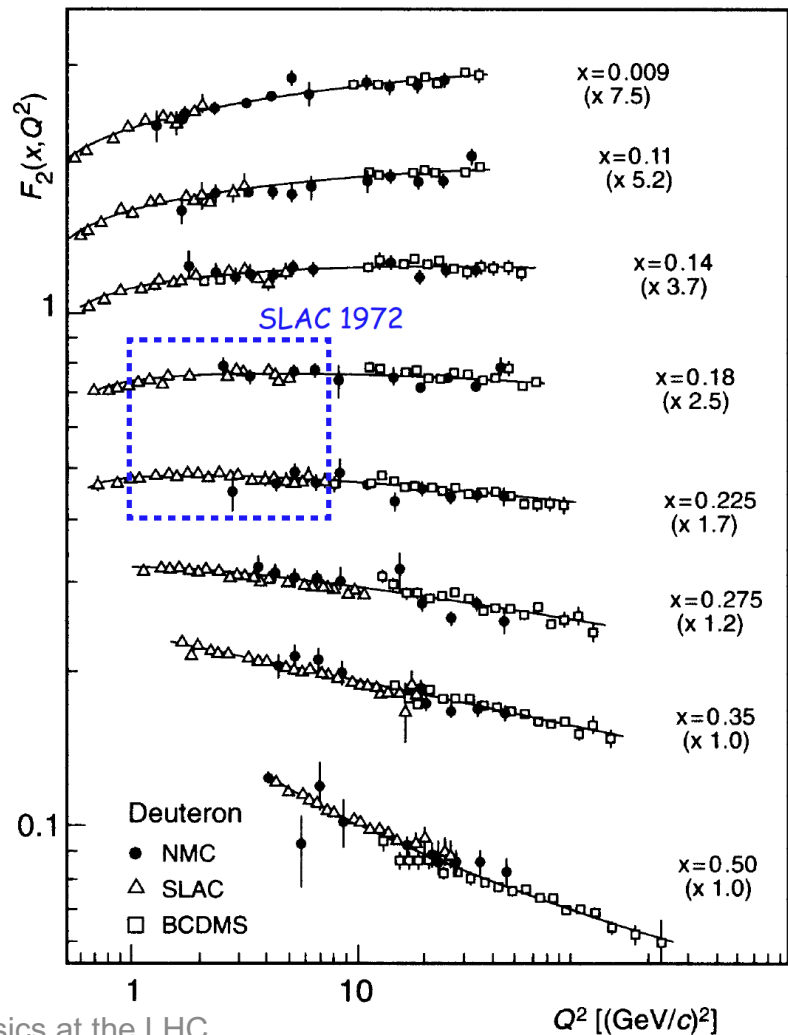
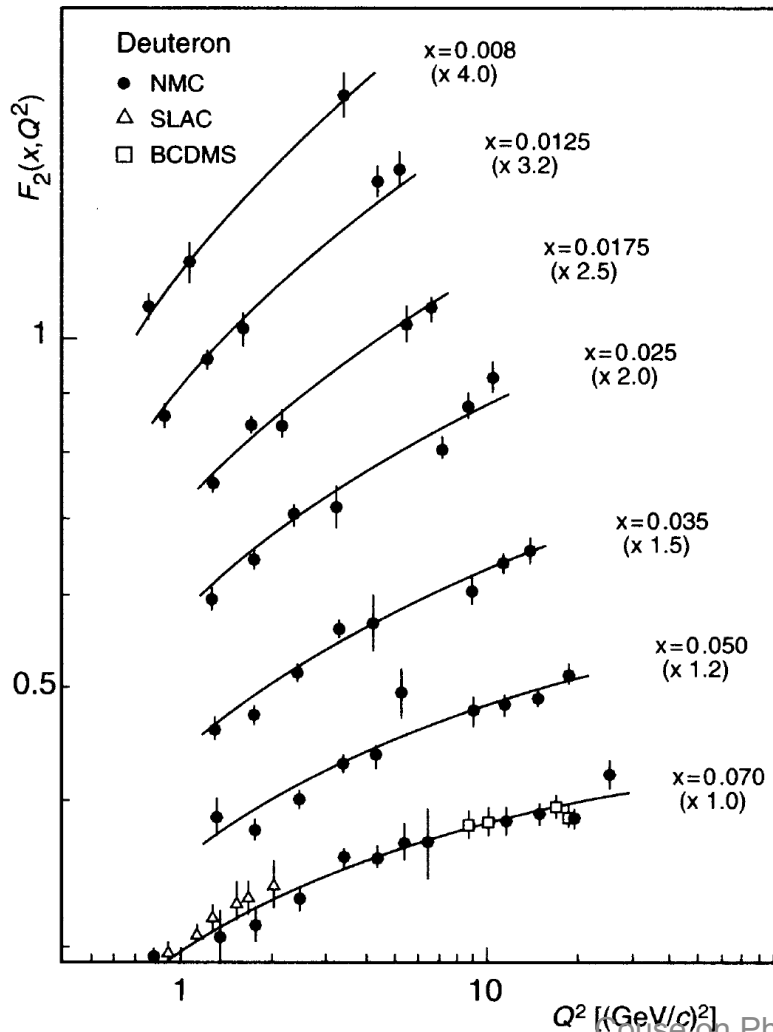
Couse on Physics at the LHC

12

x

Scaling violation

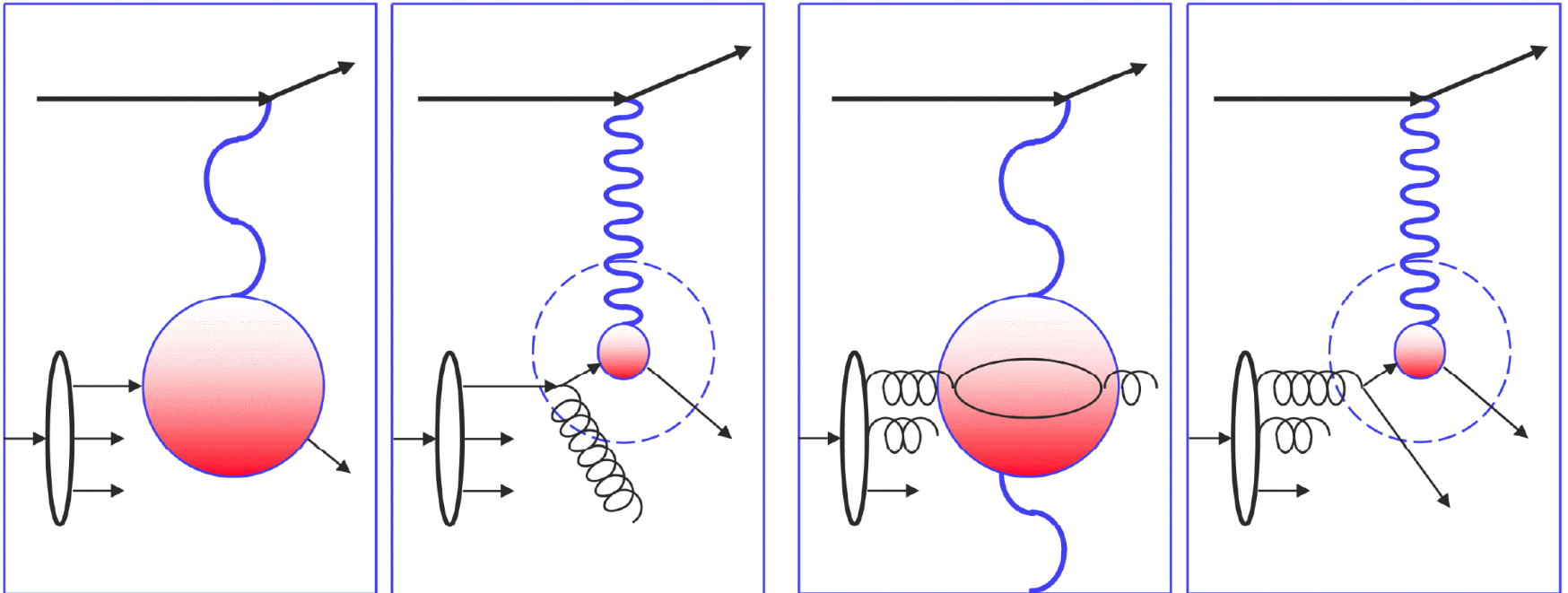
$$F_2(x, Q^2) = \sum e_q^2 x q(x, Q^2)$$



Scaling violation

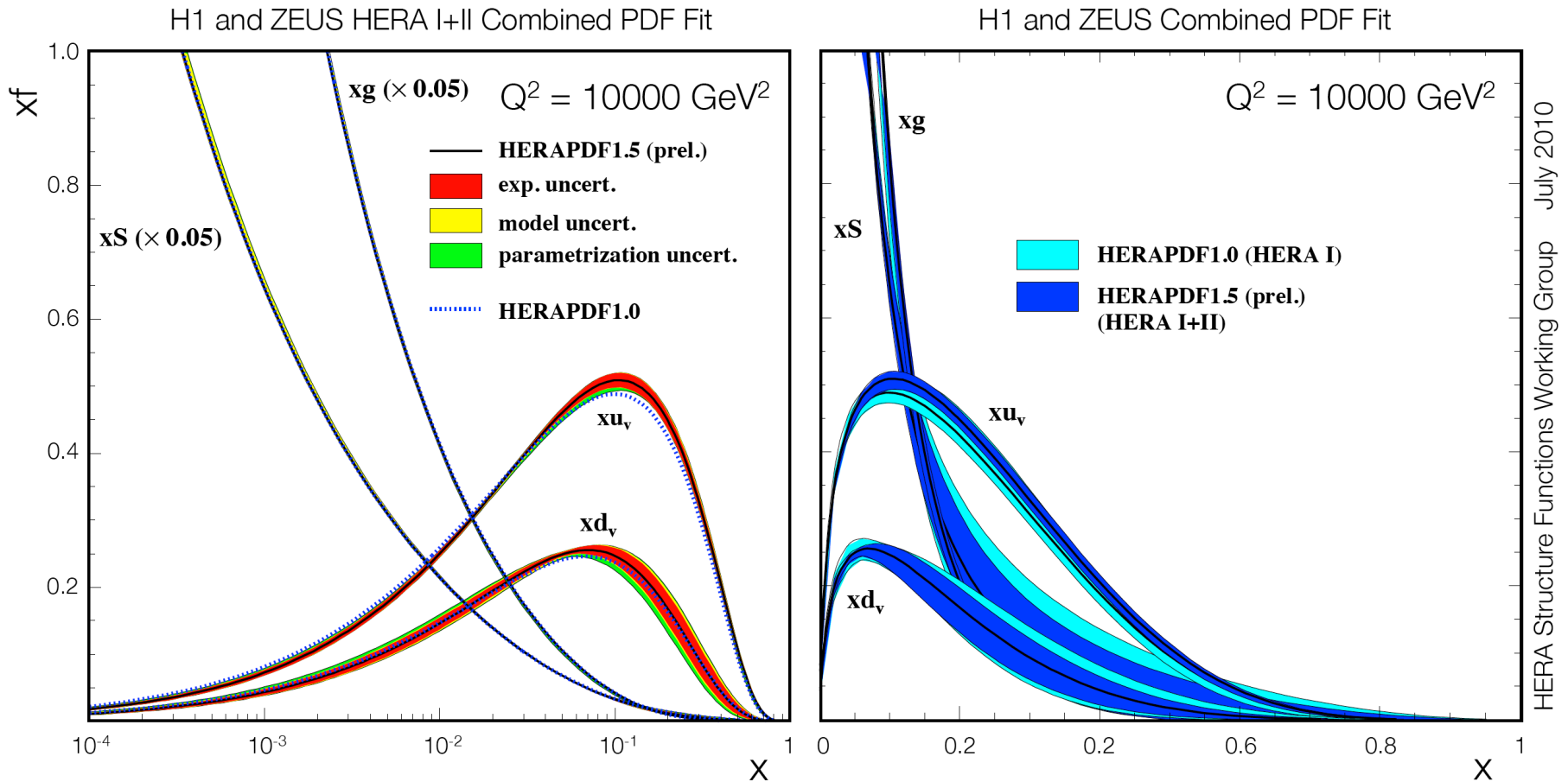
Proton quark dominated:
 $Q^2 \uparrow \Rightarrow F_2 \downarrow$ for fixed x

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

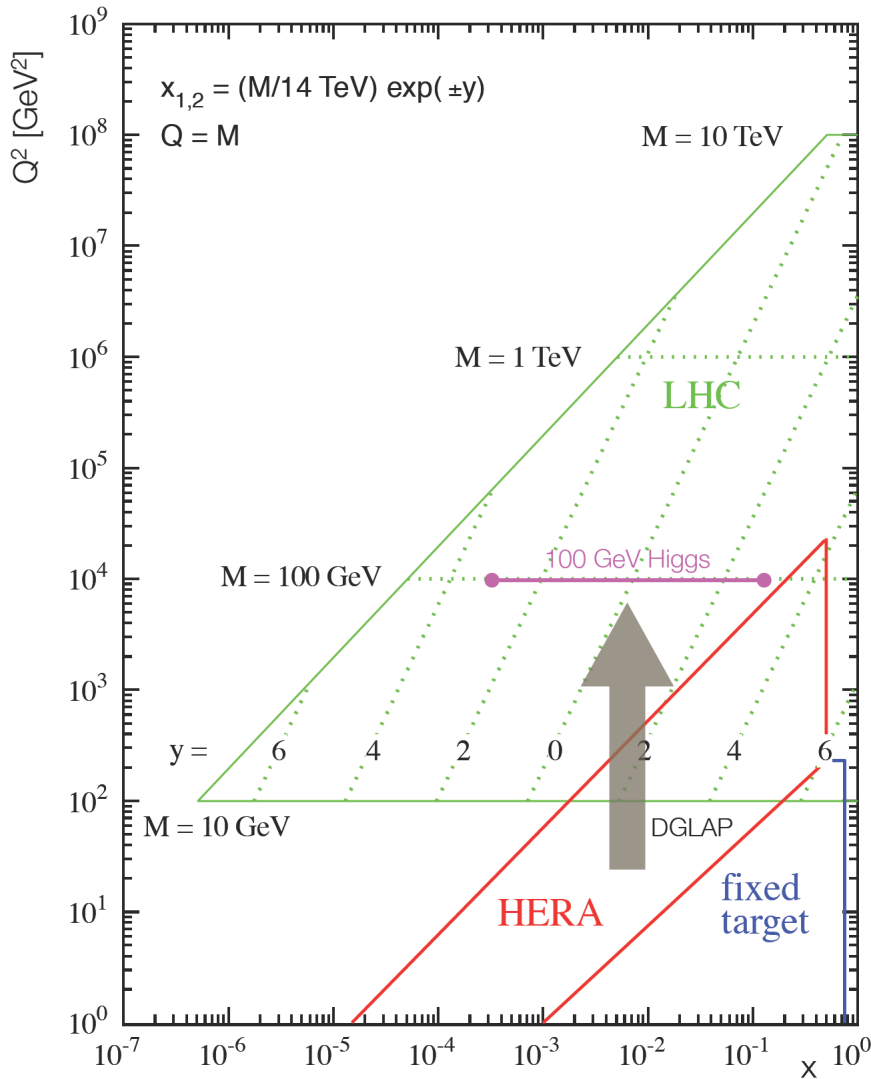


Q^2 -evolution described by DGLAP Equations

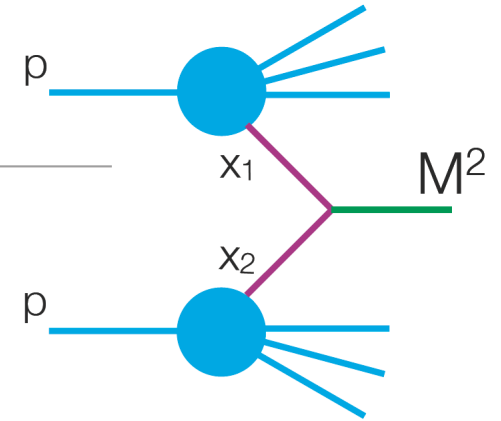
Proton parton densities



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 ($\sqrt{s} = 14 \text{ TeV}$)

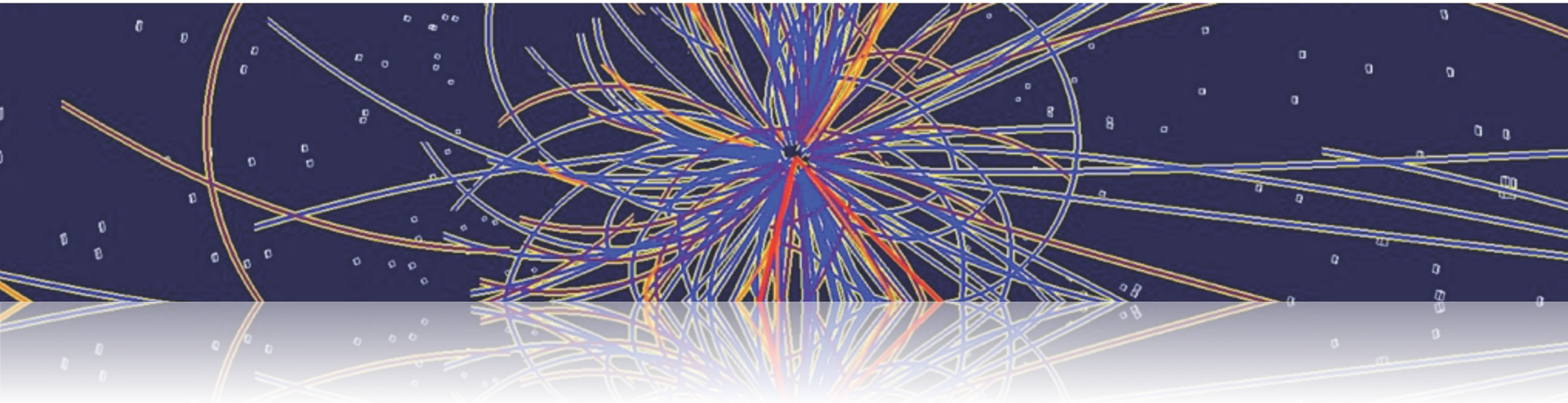
$$\langle x \rangle = \sqrt{x_1 x_2} = M/\sqrt{s}$$

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

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 ...

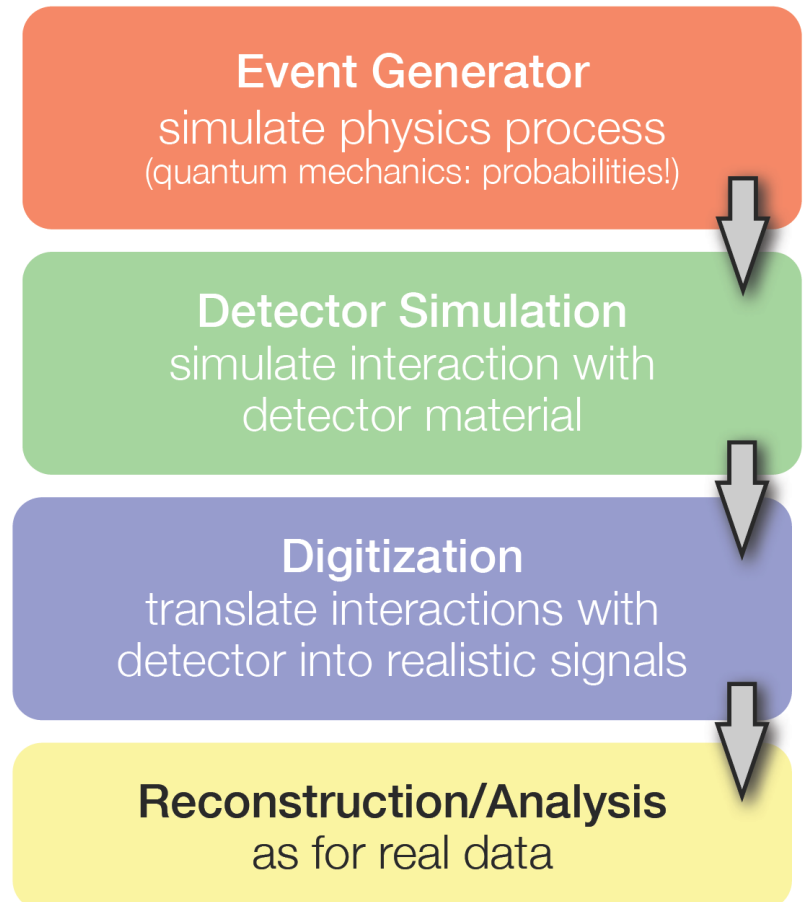
Hard partonic subprocess +
fragmentation & hadronization ...

Detector simulation:

Geant ...

interaction & response
of all produced particles ...

MC simulations in particle physics



Pythia sub-processes

No. Subprocess Hard QCD processes: 11 $f_i f_j \rightarrow f_i f_j$ 12 $f_i \bar{f}_i \rightarrow f_k \bar{f}_k$ 13 $f_i \bar{f}_i \rightarrow gg$ 28 $f_i g \rightarrow f_i g$ 53 $gg \rightarrow f_k \bar{f}_k$ 68 $gg \rightarrow gg$	No. Subprocess 36 $f_i \gamma \rightarrow f_k W^\pm$ 69 $\gamma \gamma \rightarrow W^+ W^-$ 70 $\gamma W^\pm \rightarrow Z^0 W^\pm$ Prompt photons: 14 $f_i \bar{f}_i \rightarrow g \gamma$ 18 $f_i \bar{f}_i \rightarrow \gamma \gamma$ 29 $f_i g \rightarrow f_i \gamma$ 114 $gg \rightarrow \gamma \gamma$ 115 $gg \rightarrow g \gamma$ Deeply Inel. Scatt.: 10 $f_i f_j \rightarrow f_k f_i$ 99 $\gamma^* q \rightarrow q$ Photon-induced: 33 $f_i \gamma \rightarrow f_i g$ 34 $f_i \gamma \rightarrow f_i \gamma$ 54 $g \gamma \rightarrow f_k \bar{f}_k$ 58 $\gamma \gamma \rightarrow f_k \bar{f}_k$ 131 $f_i \gamma_T^* \rightarrow f_i g$ 132 $f_i \gamma_L^* \rightarrow f_i g$ 133 $f_i \gamma_T^* \rightarrow f_i \gamma$ 134 $f_i \gamma_L^* \rightarrow f_i \gamma$ 135 $g \gamma^* \rightarrow f_i \bar{f}_i$ 136 $g \gamma_L^* \rightarrow f_i \bar{f}_i$ 137 $\gamma_T^* \gamma_L^* \rightarrow f_i \bar{f}_i$ 138 $\gamma_T^* \gamma_L^* \rightarrow f_i \bar{f}_i$ 139 $\gamma_L^* \gamma_T^* \rightarrow f_i \bar{f}_i$ 140 $\gamma_L^* \gamma_L^* \rightarrow f_i \bar{f}_i$ 80 $q_i \gamma \rightarrow q_k \pi^\pm$ Light SM Higgs: 3 $f_i \bar{f}_i \rightarrow h^0$ 24 $f_i \bar{f}_i \rightarrow Z^0 h^0$ 26 $f_i \bar{f}_j \rightarrow W^\pm h^0$ 32 $f_i g \rightarrow f_i h^0$ 102 $gg \rightarrow h^0$ 103 $\gamma \gamma \rightarrow h^0$ 110 $f_i \bar{f}_i \rightarrow \gamma h^0$ 111 $f_i \bar{f}_i \rightarrow g h^0$ 112 $f_i g \rightarrow f_i h^0$ 113 $gg \rightarrow g h^0$ 121 $gg \rightarrow Q_k \bar{Q}_k h^0$ 122 $q_i \bar{q}_i \rightarrow Q_k \bar{Q}_k h^0$ 123 $f_i f_j \rightarrow f_i f_j h^0$ 124 $f_i f_j \rightarrow f_k f_l h^0$	No. Subprocess New gauge bosons: 141 $f_i \bar{f}_i \rightarrow \gamma/Z^0/\gamma^0$ 142 $f_i \bar{f}_j \rightarrow W^{+\pm}$ 144 $f_i \bar{f}_j \rightarrow R$ Heavy SM Higgs: 5 $Z^0 Z^0 \rightarrow h^0$ 8 $W^+ W^- \rightarrow h^0$ 71 $Z_L^0 Z_L^0 \rightarrow Z_L^0 Z_L^0$ 72 $Z_L^0 Z_L^0 \rightarrow W_L^+ W_L^-$ 73 $Z_L^0 W_L^\pm \rightarrow Z_L^0 W_L^\pm$ 76 $W_L^+ W_L^- \rightarrow Z_L^0 Z_L^0$ 77 $W_L^\pm W_L^\pm \rightarrow W_L^\pm W_L^\pm$ BSM Neutral Higgs: 151 $f_i \bar{f}_i \rightarrow H^0$ 152 $gg \rightarrow H^0$ 153 $\gamma \gamma \rightarrow H^0$ 171 $f_i \bar{f}_i \rightarrow Z^0 H^0$ 172 $f_i \bar{f}_j \rightarrow W^\pm H^0$ 173 $f_i f_j \rightarrow f_i f_j H^0$ 174 $f_i f_j \rightarrow f_k f_l H^0$ 181 $gg \rightarrow Q_k \bar{Q}_k H^0$ 182 $q_i \bar{q}_i \rightarrow g Q_k \bar{Q}_k H^0$ 183 $f_i \bar{f}_i \rightarrow g H^0$ 184 $f_i g \rightarrow f_i H^0$ 185 $gg \rightarrow g H^0$ 156 $f_i \bar{f}_i \rightarrow A^0$ 157 $gg \rightarrow A^0$ 158 $\gamma \gamma \rightarrow A^0$ 176 $f_i \bar{f}_i \rightarrow Z^0 A^0$ 177 $f_i \bar{f}_j \rightarrow W^\pm A^0$ 178 $f_i f_j \rightarrow f_i f_j A^0$ 179 $f_i f_j \rightarrow f_k f_l A^0$ 186 $gg \rightarrow Q_k \bar{Q}_k A^0$ 187 $q_i \bar{q}_i \rightarrow Q_k \bar{Q}_k A^0$ 188 $f_i \bar{f}_i \rightarrow g A^0$ 189 $f_i g \rightarrow f_i A^0$ 190 $gg \rightarrow g A^0$ Charged Higgs: 143 $f_i \bar{f}_j \rightarrow H^\pm$ 161 $f_i g \rightarrow f_k H^\pm$ 401 $gg \rightarrow \bar{b} b H^\pm$ 402 $q \bar{q} \rightarrow \bar{t} b H^\pm$	No. Subprocess Higgs pairs: 297 $f_i \bar{f}_j \rightarrow H^\pm h^0$ 298 $f_i \bar{f}_j \rightarrow H^\pm H^0$ 299 $f_i \bar{f}_i \rightarrow A^0 h^0$ 300 $f_i \bar{f}_i \rightarrow A^0 H^0$ 301 $f_i \bar{f}_i \rightarrow H^+ H^-$ Leptoquarks: 145 $q_i \ell_j \rightarrow L_Q$ 162 $qg \rightarrow \ell L_Q$ 163 $gg \rightarrow L_Q \bar{L}_Q$ 164 $q_i \bar{q}_i \rightarrow L_Q \bar{L}_Q$ Technicolor: 149 $gg \rightarrow \eta_{tc}$ 191 $f_i \bar{f}_i \rightarrow \rho_{tc}^0$ 192 $f_i \bar{f}_j \rightarrow \rho_{tc}^\pm$ 193 $f_i \bar{f}_i \rightarrow \omega_{tc}^0$ 194 $f_i \bar{f}_i \rightarrow f_k \bar{f}_k$ 195 $f_i \bar{f}_j \rightarrow f_k \bar{f}_l$ 361 $f_i \bar{f}_i \rightarrow W_L^\pm \pi_{tc}^\mp$ 362 $f_i \bar{f}_i \rightarrow W_L^\pm \pi_{tc}^\mp$ 363 $f_i \bar{f}_i \rightarrow \pi_{tc}^\pm \pi_{tc}^\mp$ 364 $f_i \bar{f}_i \rightarrow \gamma \pi_{tc}^0$ 365 $f_i \bar{f}_i \rightarrow \gamma \pi_{tc}^0$ 366 $f_i \bar{f}_i \rightarrow Z^0 \pi_{tc}^0$ 367 $f_i \bar{f}_i \rightarrow Z^0 \pi_{tc}^0$ 368 $f_i \bar{f}_i \rightarrow W^\pm \pi_{tc}^\mp$ 370 $f_i \bar{f}_j \rightarrow W_L^\pm \pi_{tc}^\mp$ 371 $f_i \bar{f}_j \rightarrow W_L^\pm \pi_{tc}^\mp$ 372 $f_i \bar{f}_j \rightarrow \pi_{tc}^\pm Z_L^0$ 373 $f_i \bar{f}_j \rightarrow \pi_{tc}^\pm \pi_{tc}^0$ 374 $f_i \bar{f}_j \rightarrow \gamma \pi_{tc}^\pm$ 375 $f_i \bar{f}_j \rightarrow Z^0 \pi_{tc}^\pm$ 376 $f_i \bar{f}_j \rightarrow W^\pm \pi_{tc}^\mp$ 377 $f_i \bar{f}_j \rightarrow W^\pm \pi_{tc}^0$ 381 $q_i q_j \rightarrow q_i q_j$ 382 $q_i \bar{q}_i \rightarrow q_k \bar{q}_k$ 383 $q_i \bar{q}_i \rightarrow gg$ 384 $f_i g \rightarrow f_i g$ 385 $gg \rightarrow q_k \bar{q}_k$ 386 $gg \rightarrow gg$ 387 $f_i \bar{f}_i \rightarrow Q_k \bar{Q}_k$ 388 $gg \rightarrow Q_k \bar{Q}_k$	No. Subprocess Compositeness: 146 $e \gamma \rightarrow e^*$ 147 $dg \rightarrow d^*$ 148 $ug \rightarrow u^*$ 167 $q_i q_j \rightarrow d^* q_k$ 168 $q_i \bar{q}_j \rightarrow u^* q_k$ 169 $q_i \bar{q}_i \rightarrow e^\pm e^{*\mp}$ 165 $f_i \bar{f}_i (\rightarrow \gamma^*/Z^0) \rightarrow f_k \bar{f}_k$ 166 $f_i \bar{f}_j (\rightarrow W^\pm) \rightarrow f_k \bar{f}_l$ Extra Dimensions: 391 $f \bar{f} \rightarrow G^*$ 392 $gg \rightarrow G^*$ 393 $q \bar{q} \rightarrow g G^*$ 394 $qg \rightarrow q G^*$ 395 $gg \rightarrow g G^*$ Left-right symmetry: 341 $\ell_i \ell_j \rightarrow H_L^{\pm\pm}$ 342 $\ell_i \ell_j \rightarrow H_R^{\pm\pm}$ 343 $\ell_i^\pm \gamma \rightarrow H_L^{\pm\pm} e^\mp$ 344 $\ell_i^\pm \gamma \rightarrow H_L^{\pm\pm} e^\mp$ 345 $\ell_i^\pm \gamma \rightarrow H_L^{\pm\pm} \mu^\mp$ 346 $\ell_i^\pm \gamma \rightarrow H_R^{\pm\pm} \mu^\mp$ 347 $\ell_i^\pm \gamma \rightarrow H_L^{\pm\pm} \tau^\mp$ 348 $\ell_i^\pm \gamma \rightarrow H_R^{\pm\pm} \tau^\mp$ 349 $f_i \bar{f}_i \rightarrow H_L^+ H_L^-$ 350 $f_i \bar{f}_i \rightarrow H_R^+ H_R^-$ 351 $f_i f_j \rightarrow f_k f_l H_L^{\pm\pm}$ 352 $f_i f_j \rightarrow f_k f_l H_R^{\pm\pm}$ 353 $f_i \bar{f}_i \rightarrow Z^0$ 354 $f_i \bar{f}_j \rightarrow W_R^\pm$ SUSY: 201 $f_i \bar{f}_i \rightarrow \tilde{e}_L \tilde{e}_L^*$ 202 $f_i \bar{f}_i \rightarrow \tilde{e}_R \tilde{e}_R^*$ 203 $f_i \bar{f}_i \rightarrow \tilde{e}_L \tilde{e}_R^*$ 204 $f_i \bar{f}_i \rightarrow \tilde{\mu}_L \tilde{\mu}_L^*$ 205 $f_i \bar{f}_i \rightarrow \tilde{\mu}_R \tilde{\mu}_R^*$ 206 $f_i \bar{f}_i \rightarrow \tilde{\mu}_L \tilde{\mu}_R^*$ 207 $f_i \bar{f}_i \rightarrow \tilde{\tau}_1 \tilde{\tau}_1^*$ 208 $f_i \bar{f}_i \rightarrow \tilde{\tau}_2 \tilde{\tau}_2^*$ 209 $f_i \bar{f}_i \rightarrow \tilde{\tau}_1 \tilde{\tau}_2^*$	No. Subprocess 210 $f_i \bar{f}_j \rightarrow \tilde{\ell}_L \tilde{\nu}_\ell^* +$ 211 $f_i \bar{f}_j \rightarrow \tilde{\tau}_1 \tilde{\nu}_\tau^* +$ 212 $f_i \bar{f}_j \rightarrow \tilde{\tau}_2 \tilde{\nu}_\tau^* +$ 213 $f_i \bar{f}_i \rightarrow \tilde{\nu}_\ell \tilde{\nu}_\ell^*$ 214 $f_i \bar{f}_i \rightarrow \tilde{\nu}_\tau \tilde{\nu}_\tau^*$ 216 $f_i \bar{f}_i \rightarrow \tilde{\chi}_1 \tilde{\chi}_1$ 217 $f_i \bar{f}_i \rightarrow \tilde{\chi}_2 \tilde{\chi}_2$ 218 $f_i \bar{f}_i \rightarrow \tilde{\chi}_3 \tilde{\chi}_3$ 219 $f_i \bar{f}_i \rightarrow \tilde{\chi}_4 \tilde{\chi}_4$ 220 $f_i \bar{f}_i \rightarrow \tilde{\chi}_1 \tilde{\chi}_2$ 221 $f_i \bar{f}_i \rightarrow \tilde{\chi}_1 \tilde{\chi}_3$ 222 $f_i \bar{f}_i \rightarrow \tilde{\chi}_1 \tilde{\chi}_4$ 223 $f_i \bar{f}_i \rightarrow \tilde{\chi}_2 \tilde{\chi}_3$ 224 $f_i \bar{f}_i \rightarrow \tilde{\chi}_2 \tilde{\chi}_4$ 225 $f_i \bar{f}_i \rightarrow \tilde{\chi}_3 \tilde{\chi}_4$ 226 $f_i \bar{f}_i \rightarrow \tilde{\chi}_1^\pm \tilde{\chi}_1^\mp$ 227 $f_i \bar{f}_i \rightarrow \tilde{\chi}_2^\pm \tilde{\chi}_2^\mp$ 228 $f_i \bar{f}_i \rightarrow \tilde{\chi}_1^\pm \tilde{\chi}_2^\mp$ 229 $f_i \bar{f}_j \rightarrow \tilde{\chi}_1 \tilde{\chi}_1^\pm$ 230 $f_i \bar{f}_j \rightarrow \tilde{\chi}_2 \tilde{\chi}_1^\pm$ 231 $f_i \bar{f}_j \rightarrow \tilde{\chi}_3 \tilde{\chi}_1^\pm$ 232 $f_i \bar{f}_j \rightarrow \tilde{\chi}_4 \tilde{\chi}_1^\pm$ 233 $f_i \bar{f}_j \rightarrow \tilde{\chi}_1 \tilde{\chi}_2^\pm$ 234 $f_i \bar{f}_j \rightarrow \tilde{\chi}_2 \tilde{\chi}_2^\pm$ 235 $f_i \bar{f}_j \rightarrow \tilde{\chi}_3 \tilde{\chi}_2^\pm$ 236 $f_i \bar{f}_j \rightarrow \tilde{\chi}_4 \tilde{\chi}_2^\pm$ 237 $f_i \bar{f}_i \rightarrow \tilde{g} \tilde{\chi}_1$ 238 $f_i \bar{f}_i \rightarrow \tilde{g} \tilde{\chi}_2$ 239 $f_i \bar{f}_i \rightarrow \tilde{g} \tilde{\chi}_3$ 240 $f_i \bar{f}_i \rightarrow \tilde{g} \tilde{\chi}_4$ 241 $f_i \bar{f}_j \rightarrow \tilde{g} \tilde{\chi}_1^\pm$ 242 $f_i \bar{f}_j \rightarrow \tilde{g} \tilde{\chi}_2^\pm$ 243 $f_i \bar{f}_i \rightarrow \tilde{g} \tilde{g}$ 244 $gg \rightarrow \tilde{g} \tilde{g}$ 246 $f_i g \rightarrow \tilde{q}_i L \tilde{\chi}_1$ 247 $f_i g \rightarrow \tilde{q}_i R \tilde{\chi}_1$ 248 $f_i g \rightarrow \tilde{q}_i L \tilde{\chi}_2$ 249 $f_i g \rightarrow \tilde{q}_i R \tilde{\chi}_2$	No. Subprocess 250 $f_i g \rightarrow \tilde{q}_i L \tilde{\chi}_3$ 251 $f_i g \rightarrow \tilde{q}_i R \tilde{\chi}_3$ 252 $f_i g \rightarrow \tilde{q}_i L \tilde{\chi}_4$ 253 $f_i g \rightarrow \tilde{q}_i R \tilde{\chi}_4$ 254 $f_i g \rightarrow \tilde{q}_j L \tilde{\chi}_1^\pm$ 256 $f_i g \rightarrow \tilde{q}_j L \tilde{\chi}_2^\pm$ 258 $f_i g \rightarrow \tilde{q}_i L \tilde{g}$ 259 $f_i g \rightarrow \tilde{q}_i R \tilde{g}$ 261 $f_i \bar{f}_i \rightarrow \tilde{t}_1 \tilde{t}_1^*$ 262 $f_i \bar{f}_i \rightarrow \tilde{t}_2 \tilde{t}_2^*$ 263 $f_i \bar{f}_i \rightarrow \tilde{t}_1 \tilde{t}_2^* +$ 264 $gg \rightarrow \tilde{t}_1 \tilde{t}_1^*$ 265 $gg \rightarrow \tilde{t}_2 \tilde{t}_2^*$ 271 $f_i f_j \rightarrow \tilde{q}_i L \tilde{q}_j L$ 272 $f_i f_j \rightarrow \tilde{q}_i R \tilde{q}_j R$ 273 $f_i f_j \rightarrow \tilde{q}_i L \tilde{q}_j R +$ 274 $f_i f_j \rightarrow \tilde{q}_i L \tilde{q}_j L$ 275 $f_i f_j \rightarrow \tilde{q}_i R \tilde{q}_j R$ 276 $f_i f_j \rightarrow \tilde{q}_i L \tilde{q}_j R +$ 277 $f_i \bar{f}_i \rightarrow \tilde{q}_j L \tilde{q}_j^*$ 278 $f_i \bar{f}_i \rightarrow \tilde{q}_j R \tilde{q}_j^*$ 279 $gg \rightarrow \tilde{q}_i L \tilde{q}_i^*$ 280 $gg \rightarrow \tilde{q}_i R \tilde{q}_i^*$ 281 $b q_i \rightarrow \tilde{b}_1 \tilde{q}_i L$ 282 $b q_i \rightarrow \tilde{b}_2 \tilde{q}_i R$ 283 $b q_i \rightarrow \tilde{b}_1 \tilde{q}_i R +$ 284 $b \bar{q}_i \rightarrow \tilde{b}_1 \tilde{q}_i^*$ 285 $b \bar{q}_i \rightarrow \tilde{b}_2 \tilde{q}_i^*$ 286 $b \bar{q}_i \rightarrow \tilde{b}_1 \tilde{q}_i^* R +$ 287 $f_i \bar{f}_i \rightarrow \tilde{b}_1 \tilde{b}_1^*$ 288 $f_i \bar{f}_i \rightarrow \tilde{b}_2 \tilde{b}_2^*$ 289 $gg \rightarrow \tilde{b}_1 \tilde{b}_1^*$ 290 $gg \rightarrow \tilde{b}_2 \tilde{b}_2^*$ 291 $bb \rightarrow \tilde{b}_1 \tilde{b}_1$ 292 $bb \rightarrow \tilde{b}_2 \tilde{b}_2$ 293 $bb \rightarrow \tilde{b}_1 \tilde{b}_2$ 294 $bg \rightarrow \tilde{b}_1 \tilde{g}$ 295 $bg \rightarrow \tilde{b}_2 \tilde{g}$ 296 $b \bar{b} \rightarrow \tilde{b}_1 \tilde{b}_2^* +$
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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:

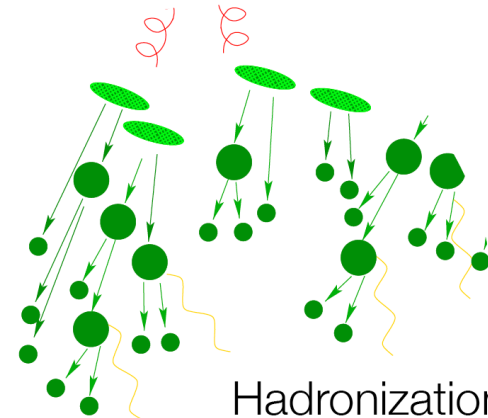
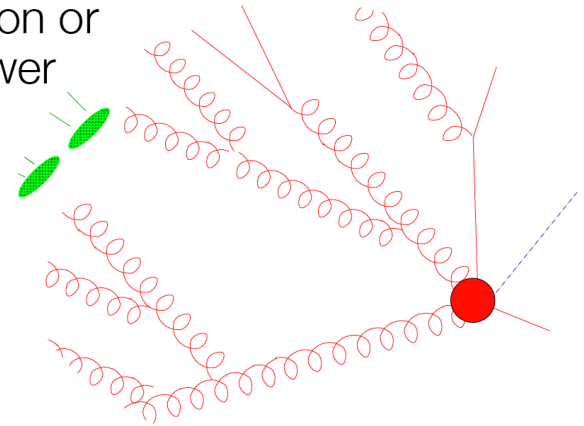
Parton shower forms hadrons

[non-perturbative, only models]

Decay of unstable hadrons

[perturbative QCD, electroweak theory]

Fragmentation or
Parton Shower



Hadronization &
Decays

Detector simulation

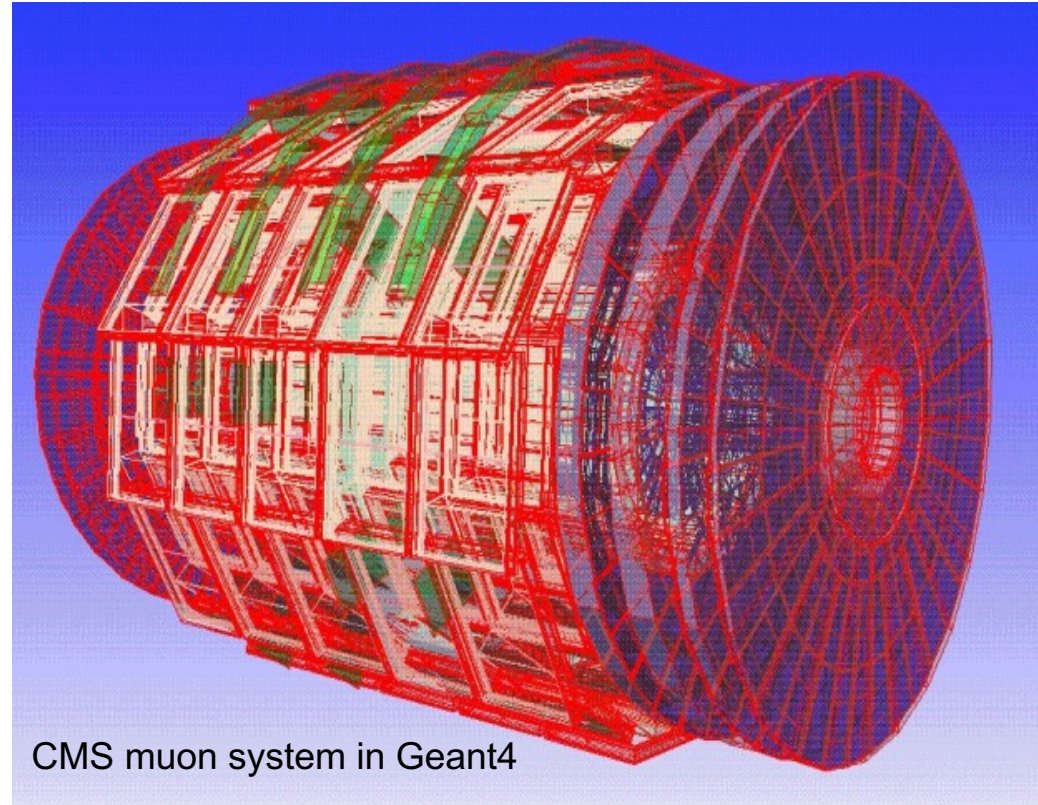
GEANT

Geometry And Tracking

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

Tracking of all particles through
detector material ...

→ **Detector response**

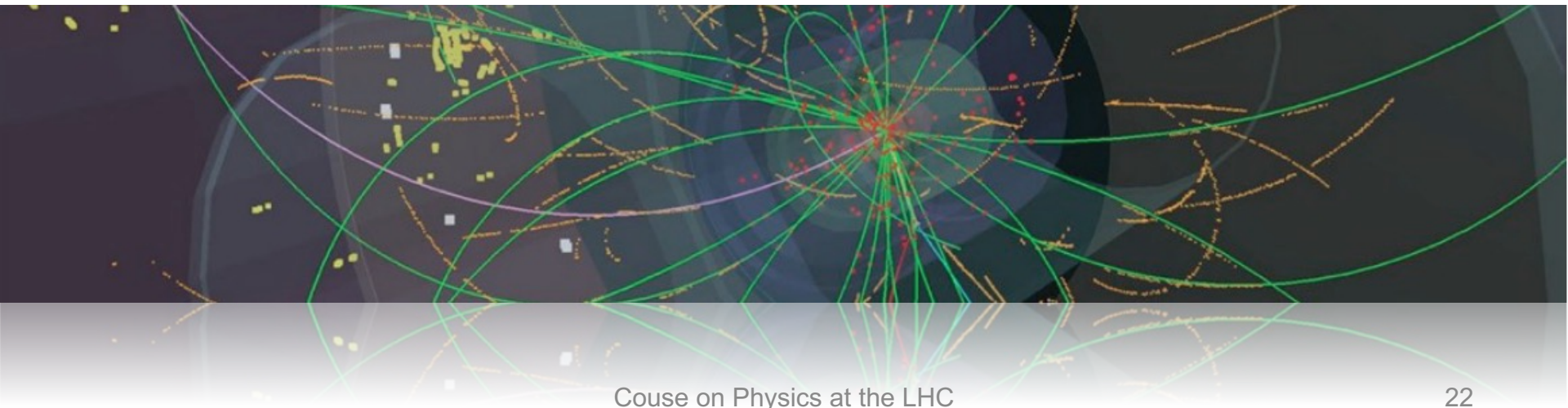


CMS muon system in Geant4

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

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

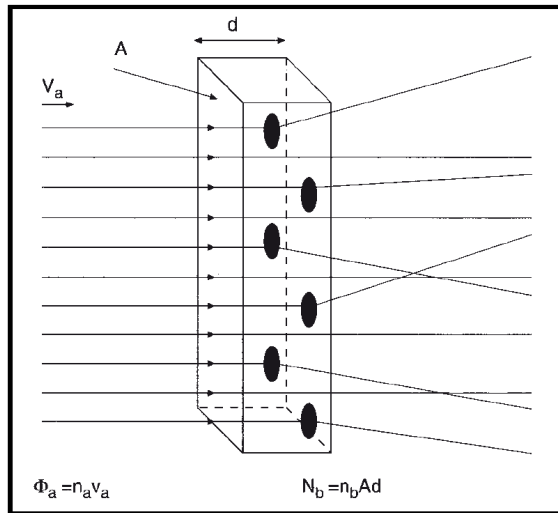
Luminosity

determined by accelerator,
triggers, ...

Efficiency

many factors, optimized
by experimentalist

Cross section & Luminosity



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

Φ_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
 σ_a : effective area of single scattering center

$$L = \Phi_a \cdot N_b$$

L : luminosity

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

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

Collider experiment:

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

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

LHC:

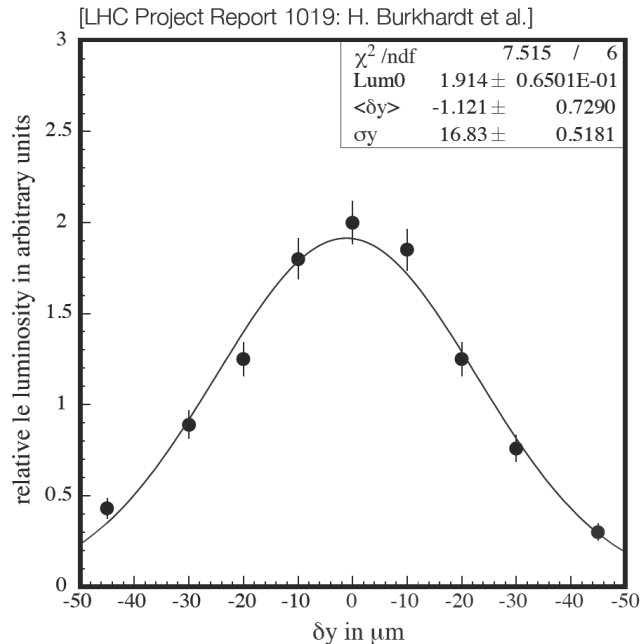
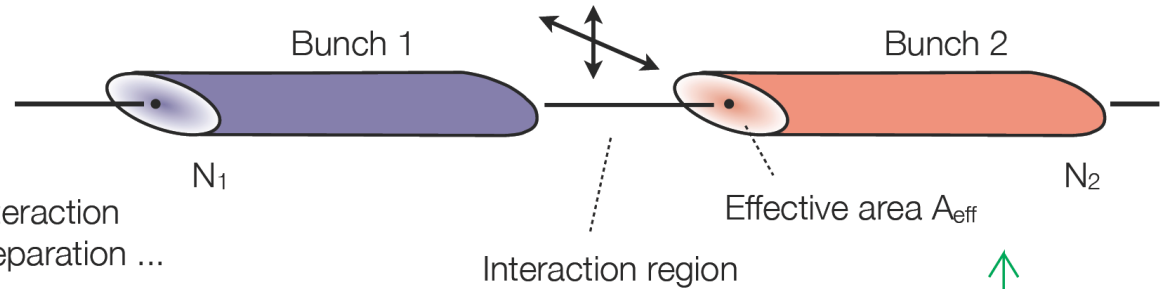
$N_x \sim 10^{11}$
 $A \sim .0005 \text{ mm}^2$
 $n \sim 2800$
 $f \sim 11 \text{ kHz}$
 $L \sim 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$

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
 σ_x : standard deviation of beam profile in x
 σ_y : standard deviation of beam profile in y

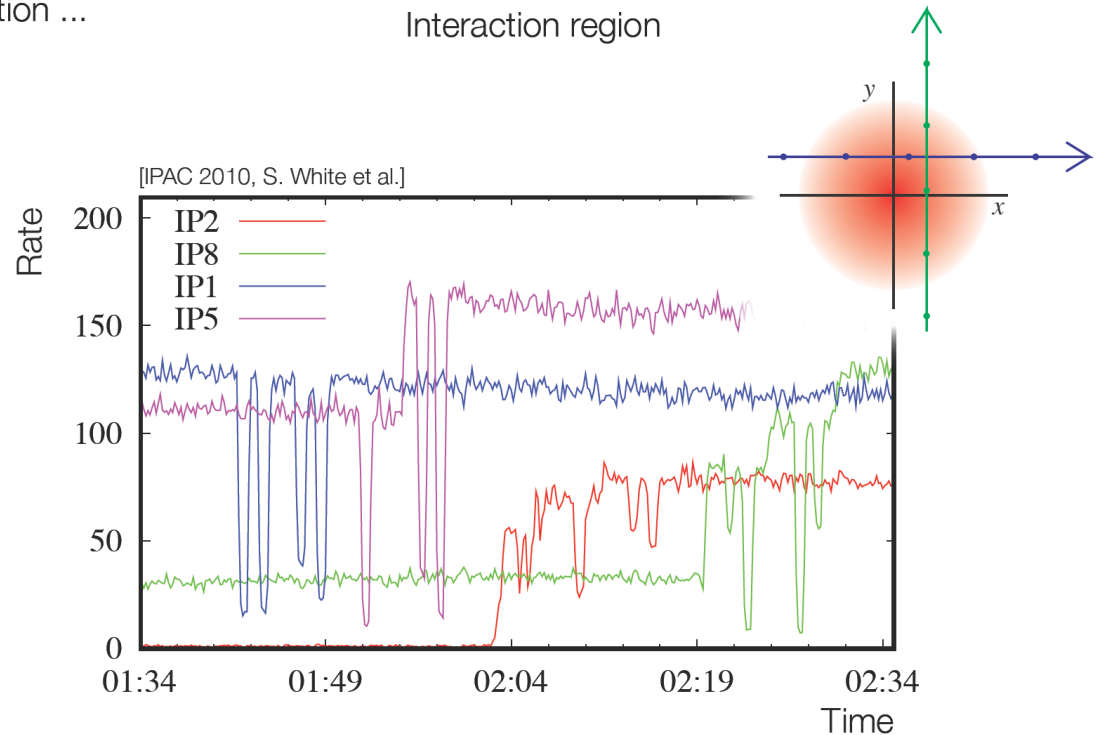
Van-der-Meer separation scan

Determine beam size ...

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

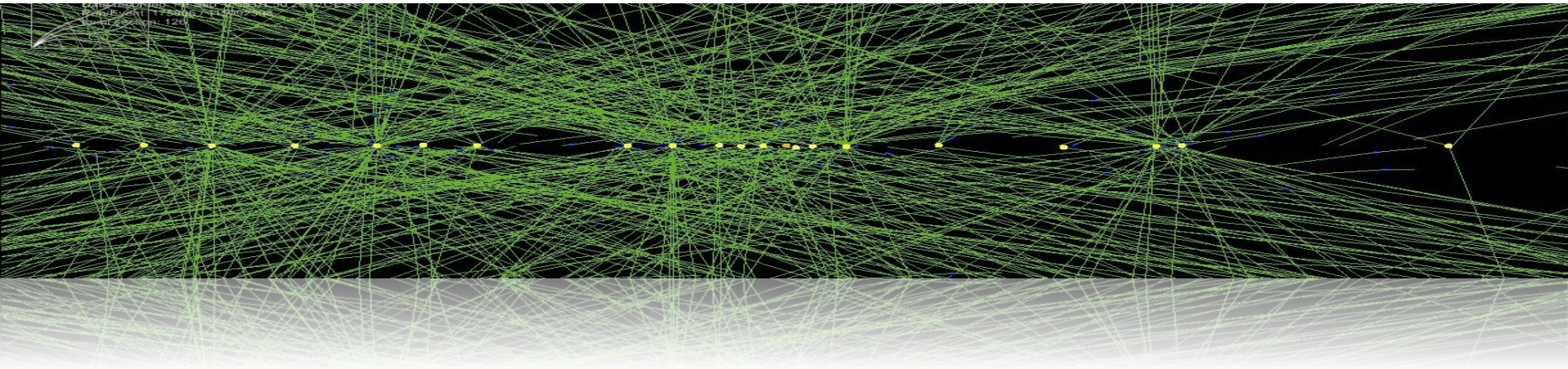


$$\frac{L}{L_0} = \exp \left[- \left(\frac{\delta_x}{2\sigma_x} \right)^2 - \left(\frac{\delta_y}{2\sigma_y} \right)^2 \right]$$



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

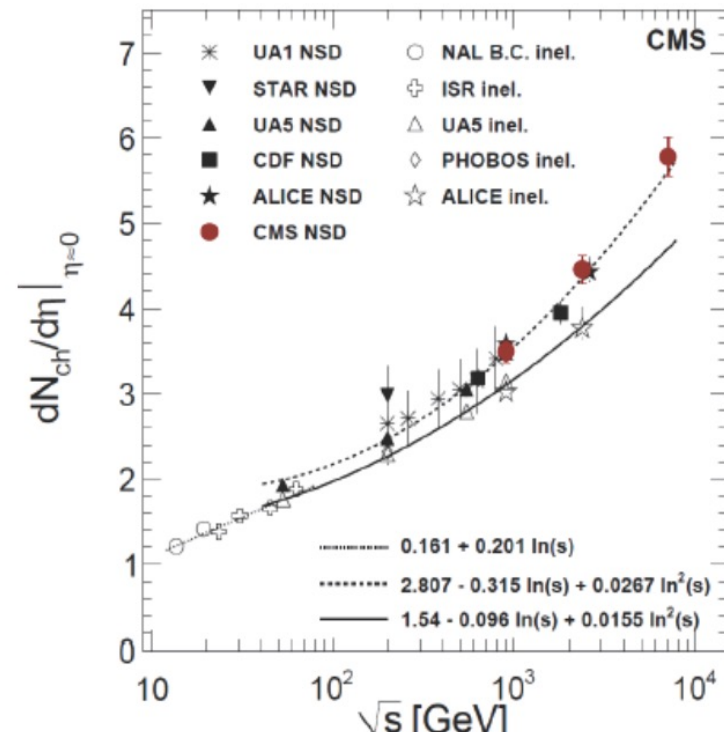
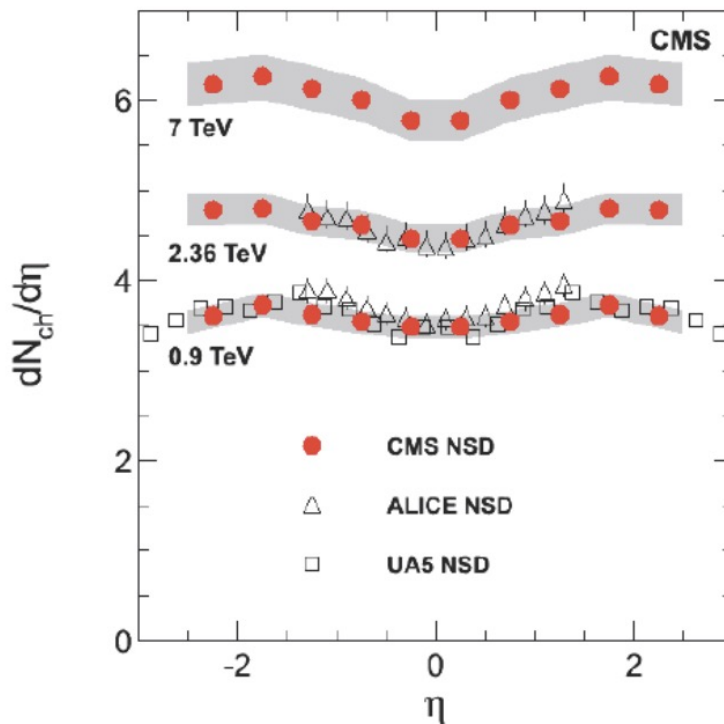
Minimum bias events



Characteristics of inelastic p-p collisions

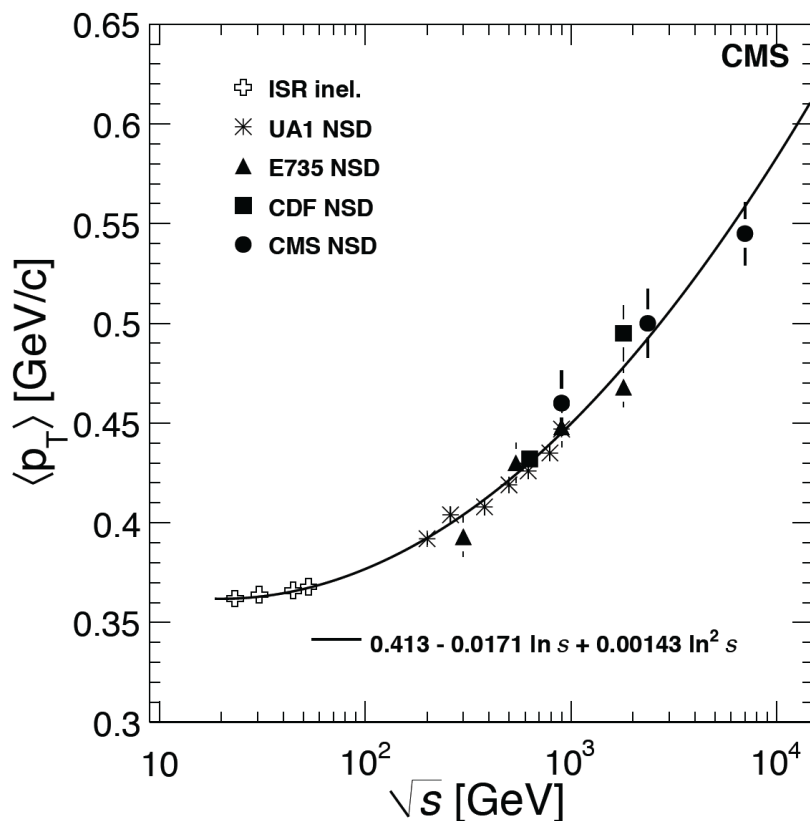
Particle density in minimum bias events

Soft QCD (PT threshold on tracks: 50 MeV)

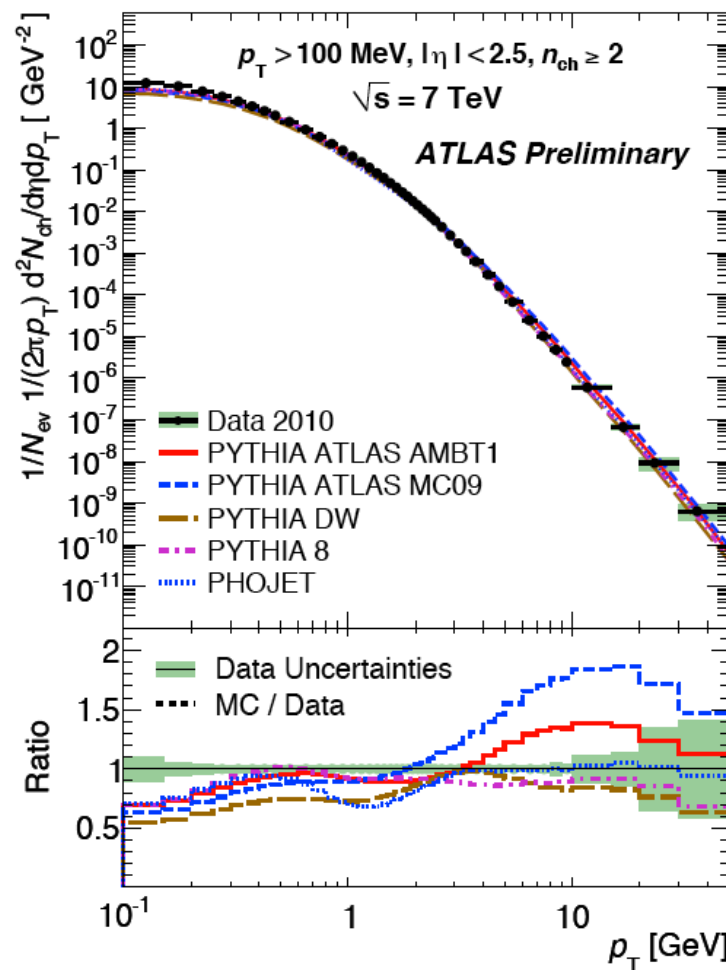


Charged particle p_T spectrum

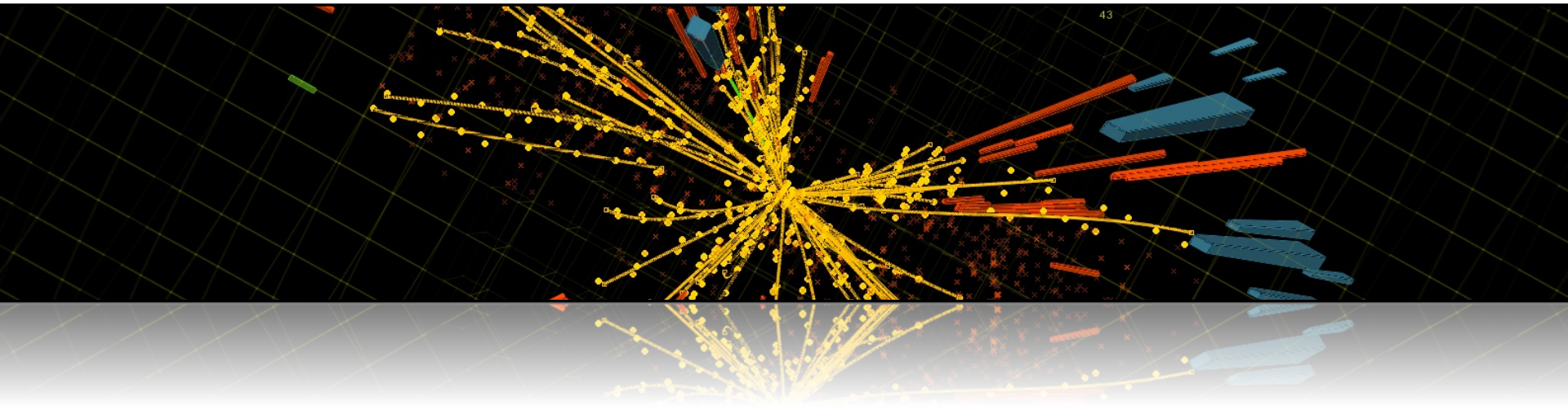
$$\begin{aligned} \langle p_T \rangle &= 0.545 \\ &\pm 0.005 \text{ (stat.)} \\ &\pm 0.015 \text{ (syst.) GeV/c} \end{aligned}$$



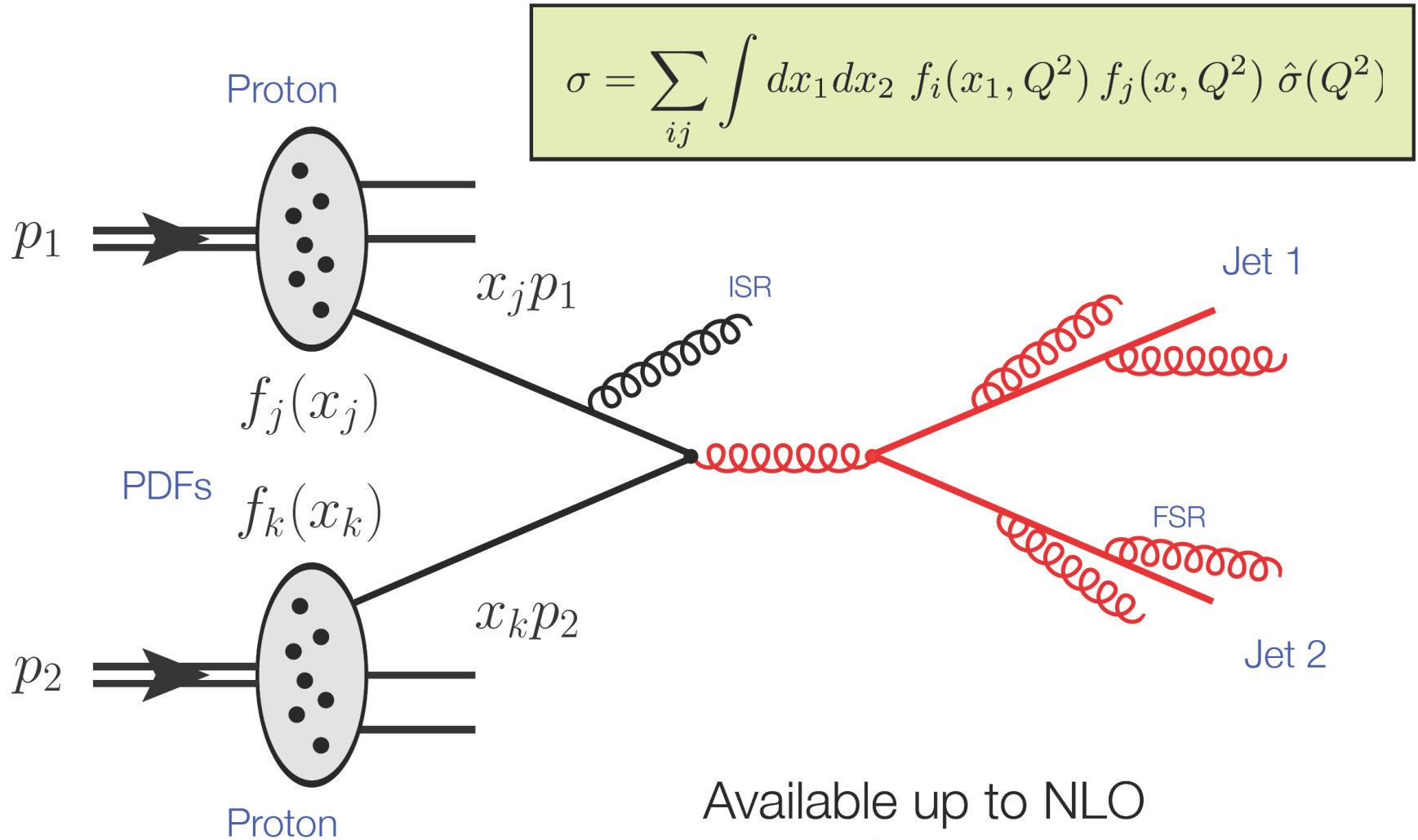
$$\begin{aligned} dN_{ch}/dp_T \\ p_T > 100 \text{ MeV} \\ |\eta| < 2.5 \\ N_{ch} \geq 2 \end{aligned}$$



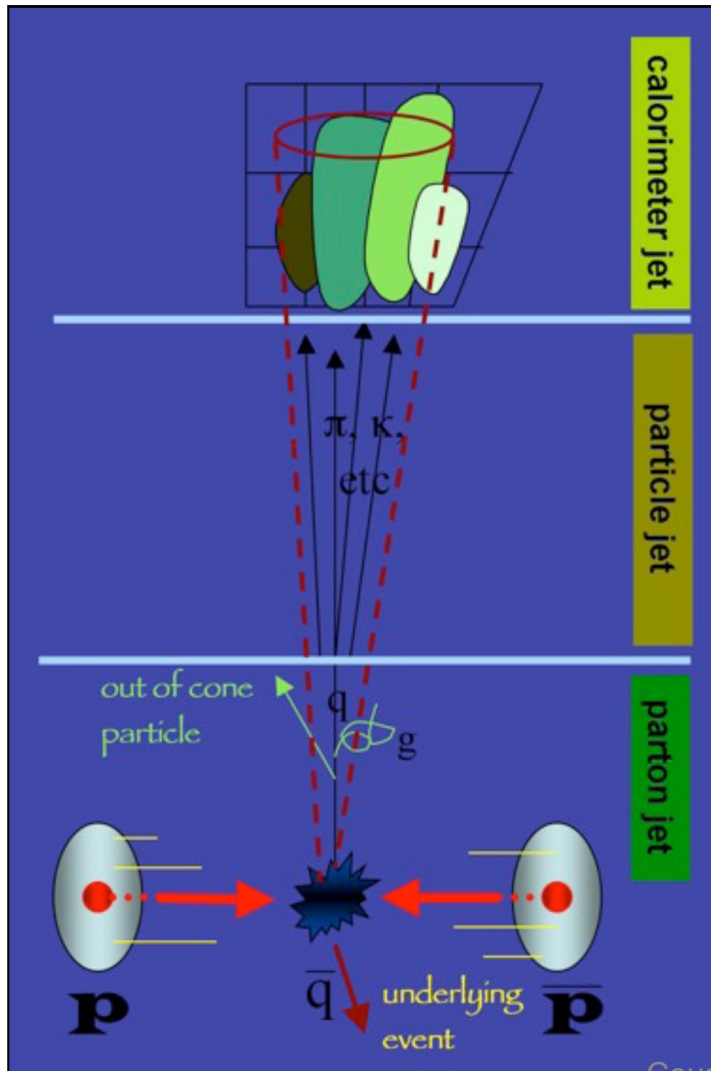
Jet physics



Jet production @ LHC



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 ...

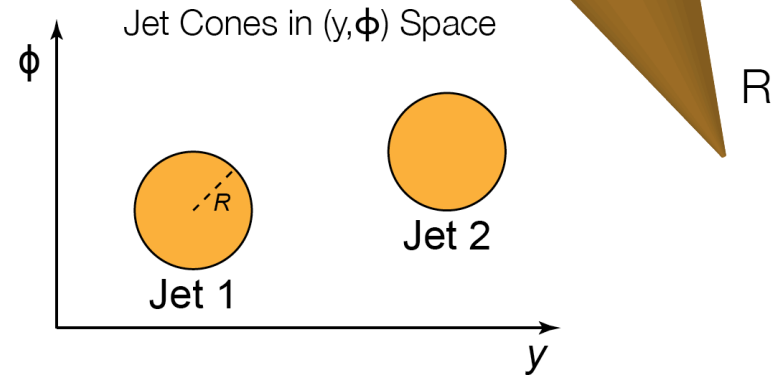
Needs Calibration

Jet reconstruction

Iterative cone algorithms:

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

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



Sequential recombination algorithms:

Define distance measure d_{ij} ...

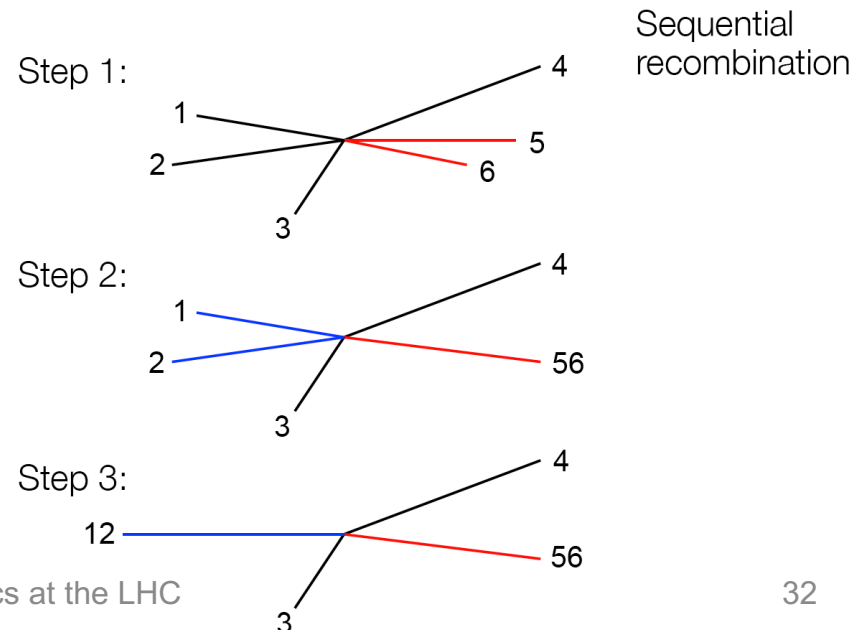
Calculate d_{ij} for all pairs of objects ...

Combine particles with minimum d_{ij} below cut ...

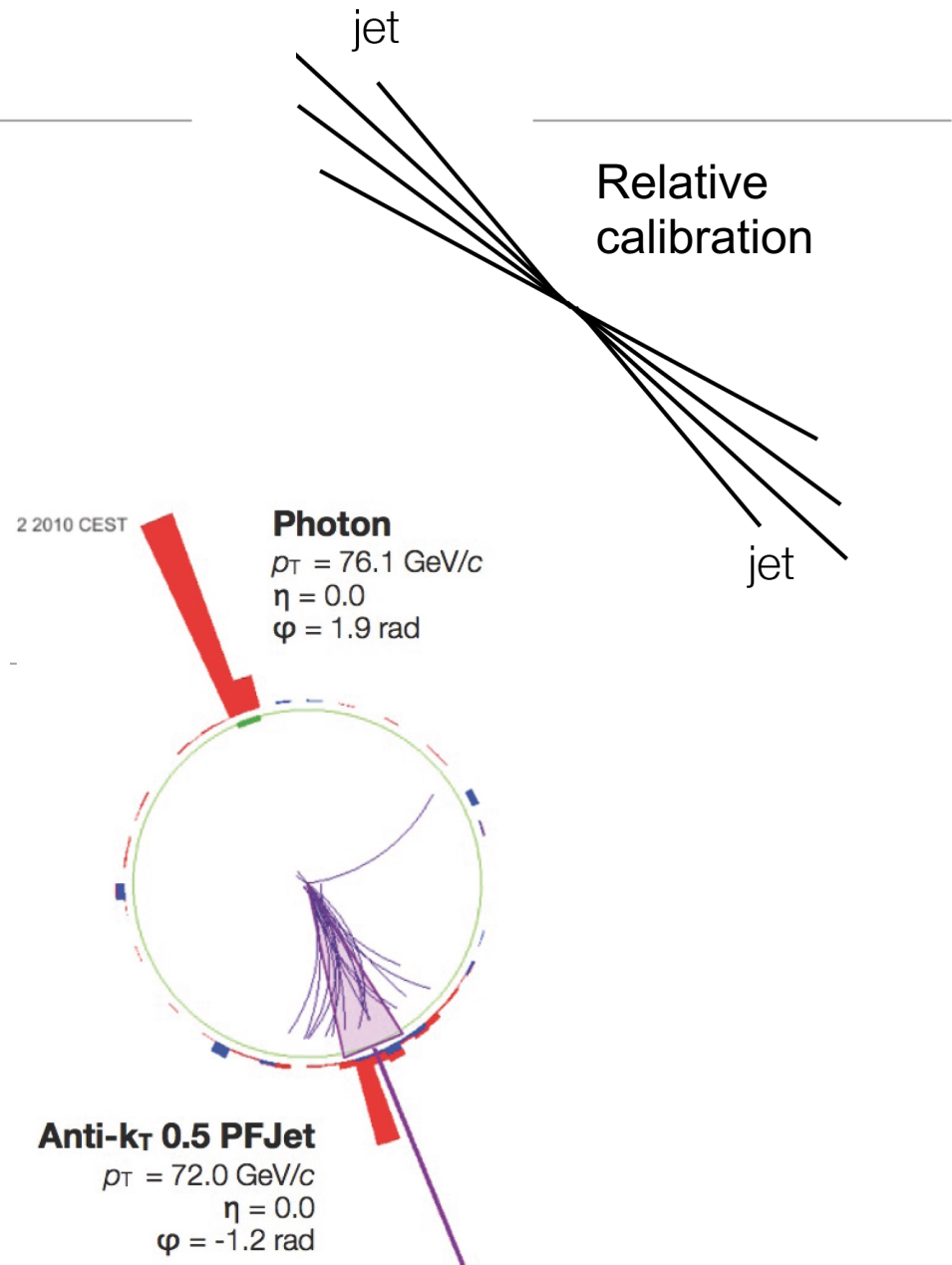
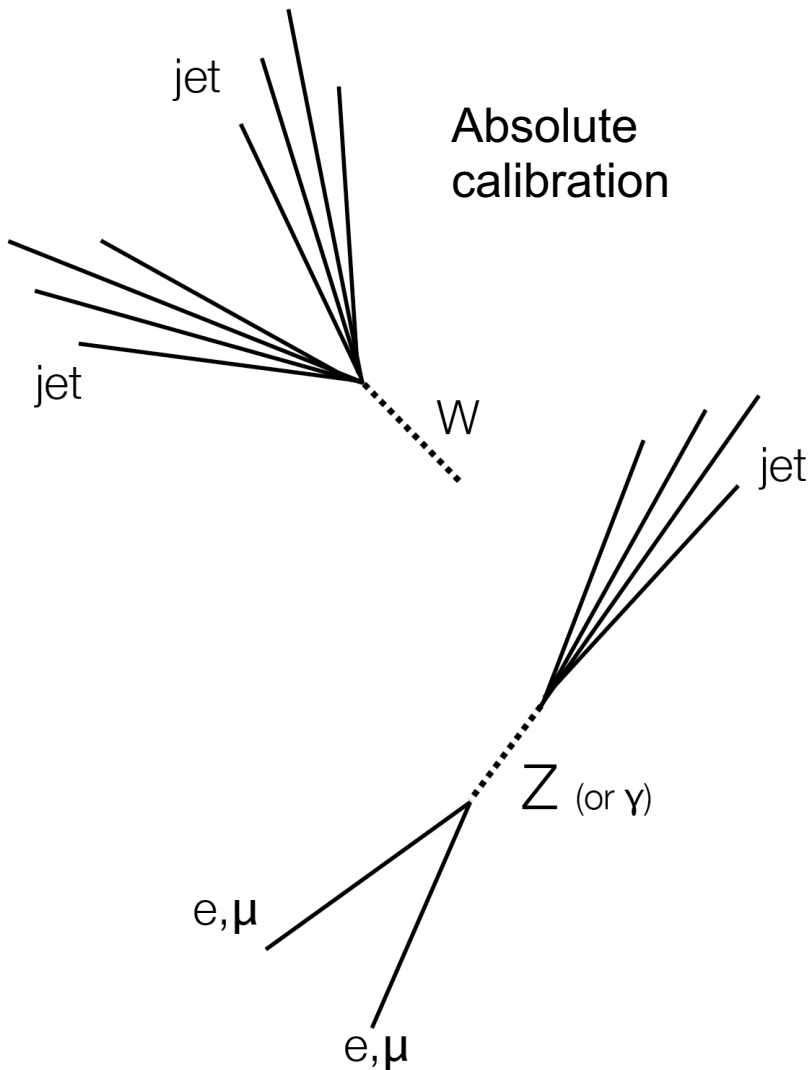
Stop if minimum d_{ij} above cut ...

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

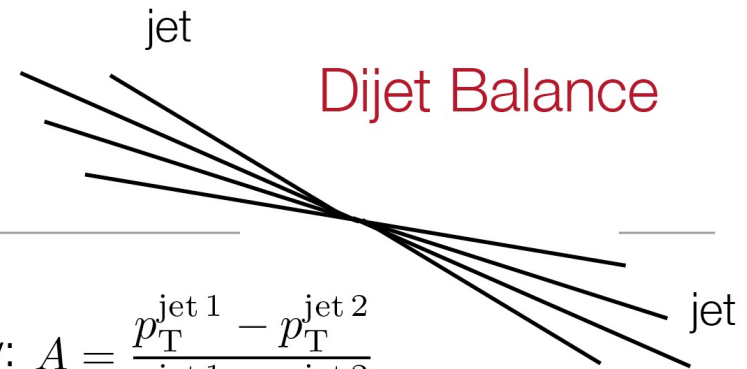
$$d_{ij} = \min(k_{T,i}^2, k_{T,j}^2) \frac{\Delta R_{ij}}{R}$$



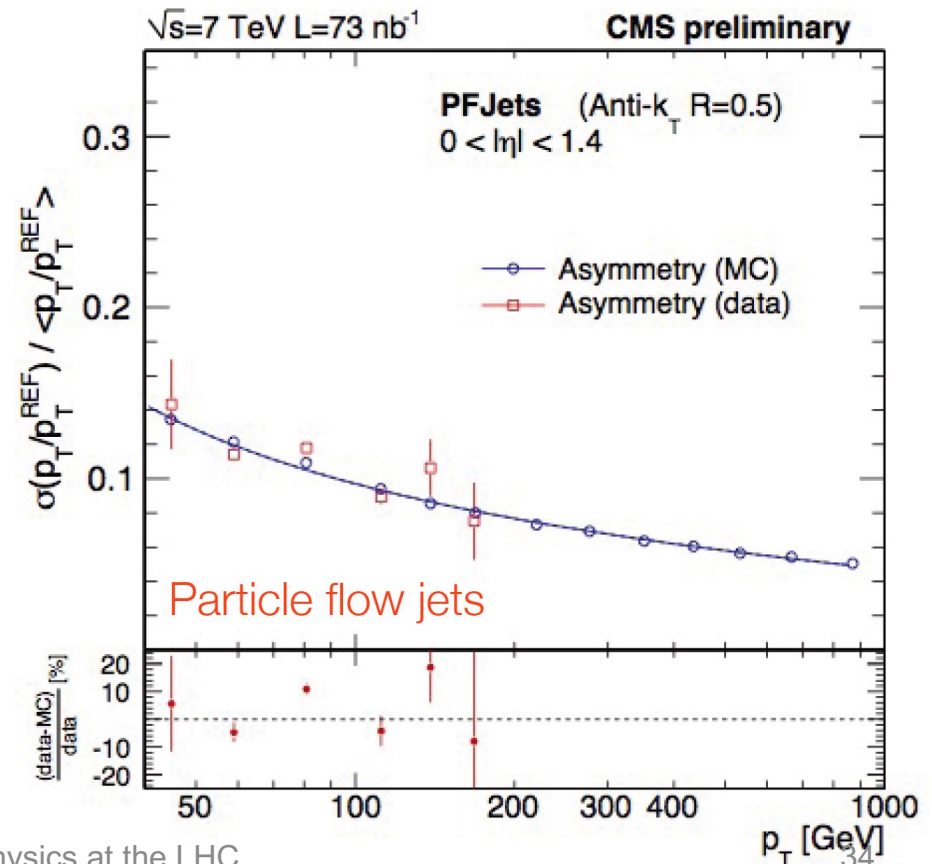
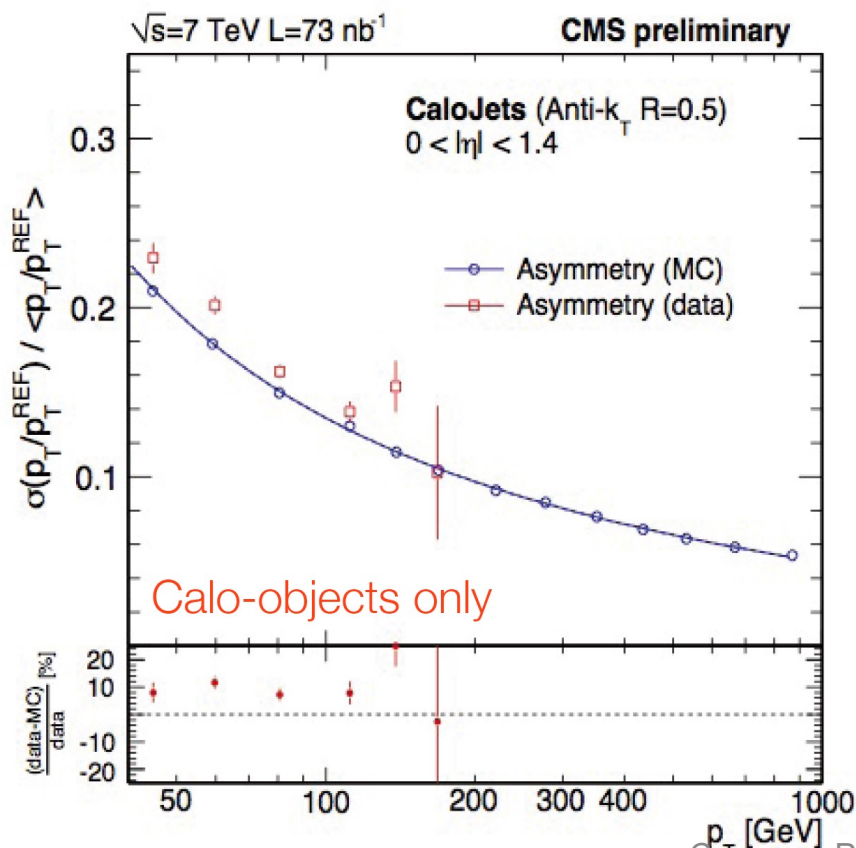
Jet energy calibration



Jet energy resolution



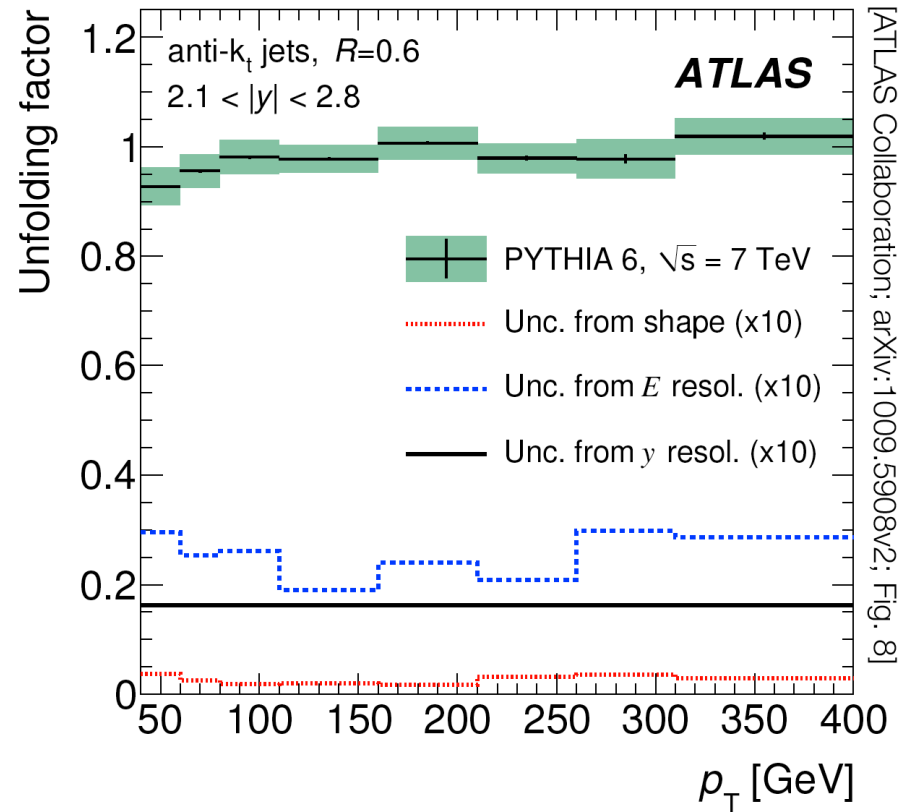
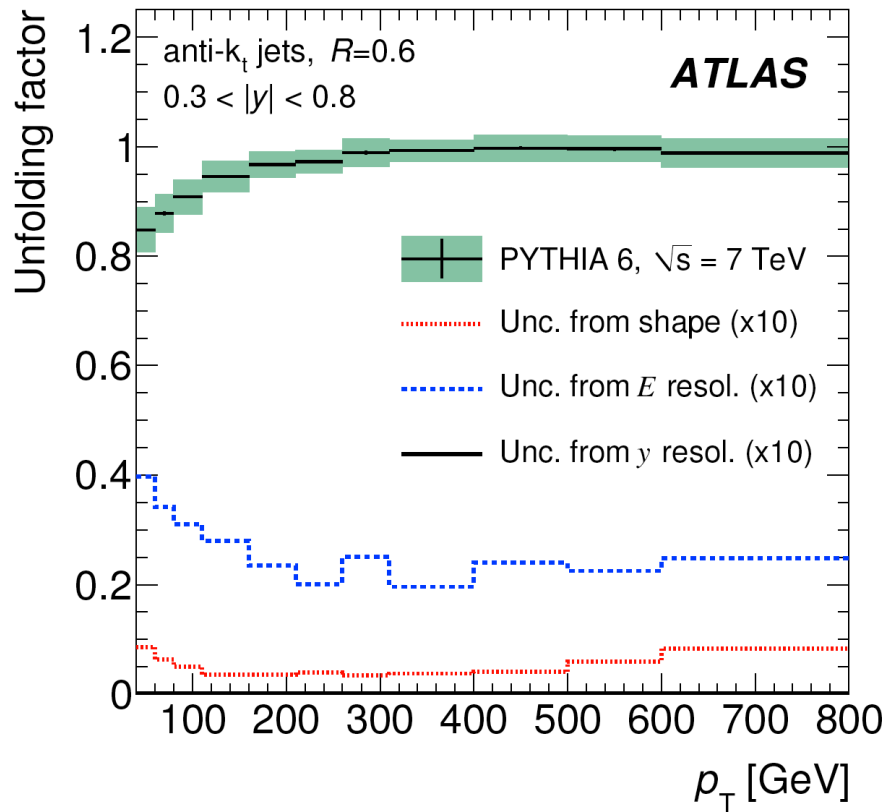
Resolution: $\frac{\sigma(p_T)}{p_T} = \sqrt{2}\sigma_A$ using p_T asymmetry: $A = \frac{p_T^{\text{jet } 1} - p_T^{\text{jet } 2}}{p_T^{\text{jet } 1} + p_T^{\text{jet } 2}}$



Resolution unfolding

Measured spectrum =
Real spectrum \otimes Experim. resolution

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



[ATLAS Collaboration; arXiv:1009.5908v2; Fig. 8]

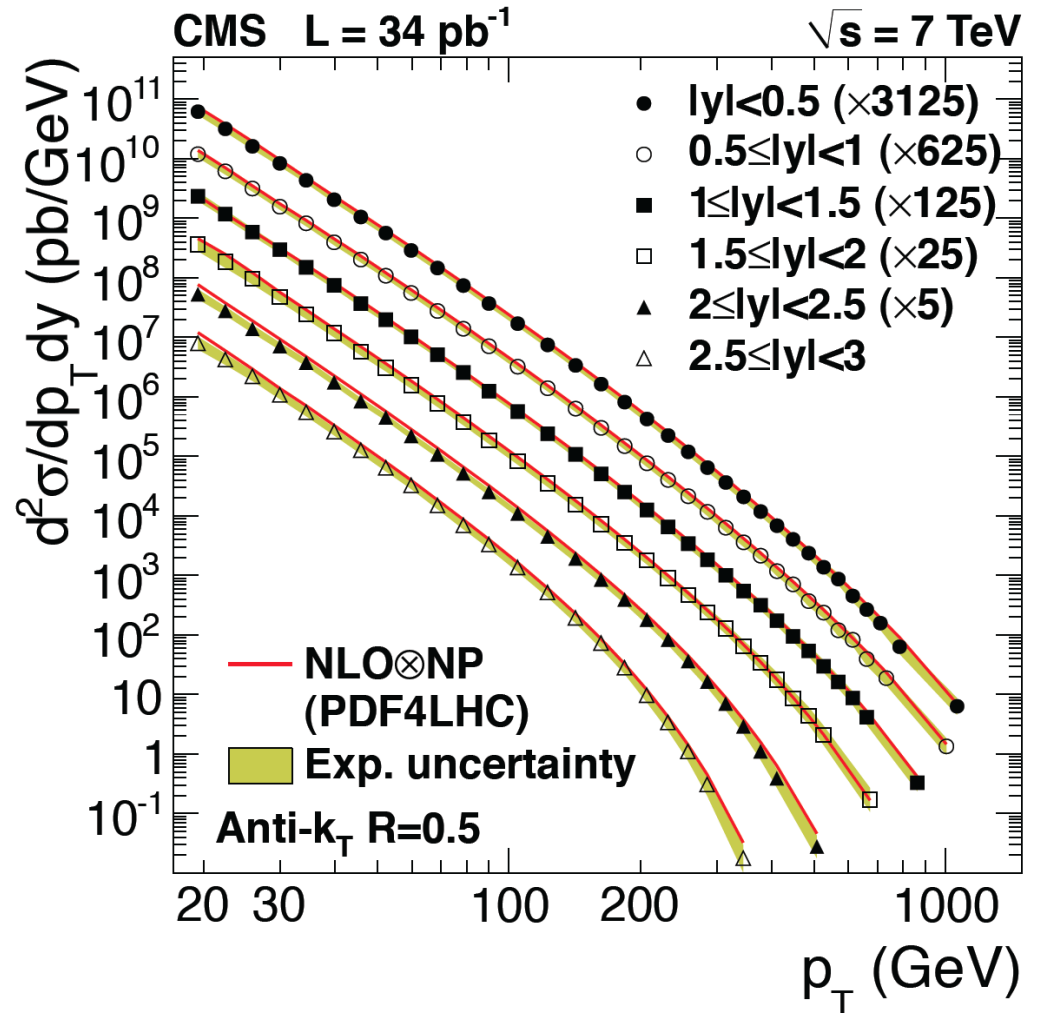
Inclusive jet cross-section

Cross section is huge
(~ Tevatron x 100)

Very good agreement with
NLO QCD over nine orders of
magnitude

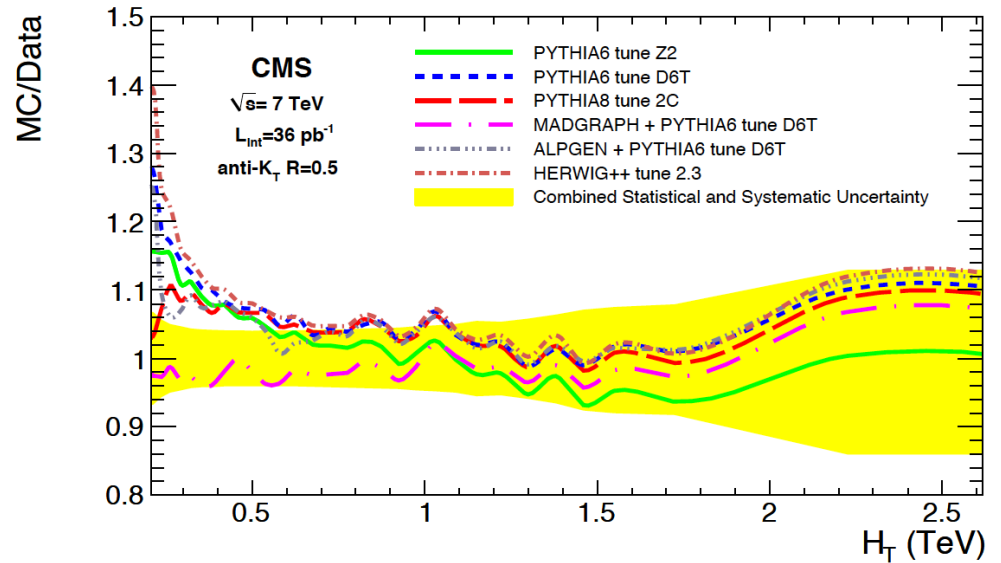
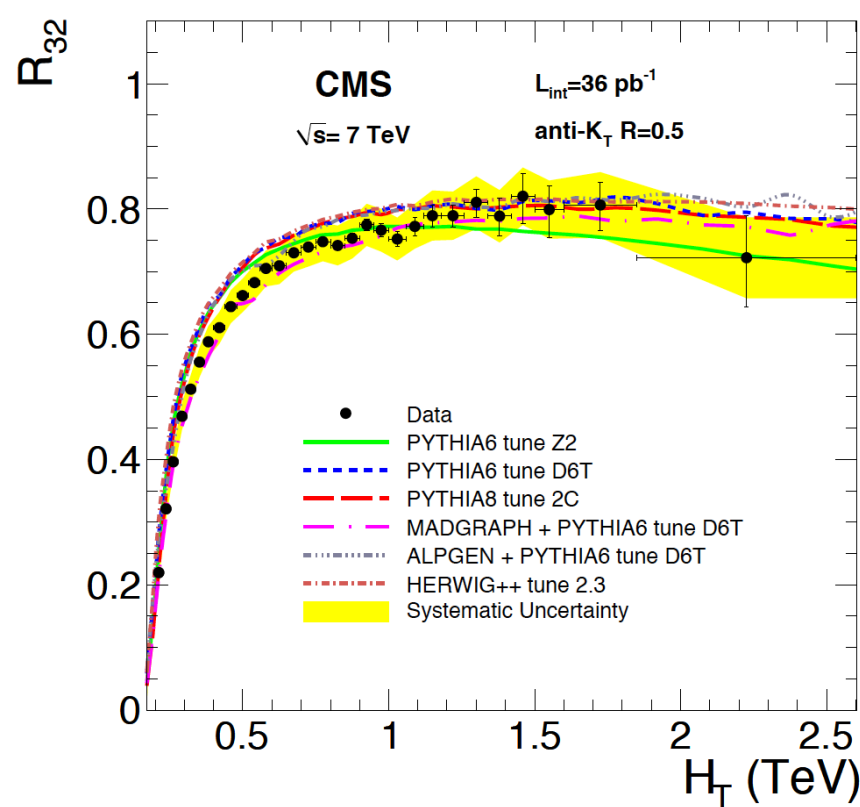
PT extending from 20 to 500
GeV

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



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

hep-ex 1106.0647, PLB 702 (2011) 336



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

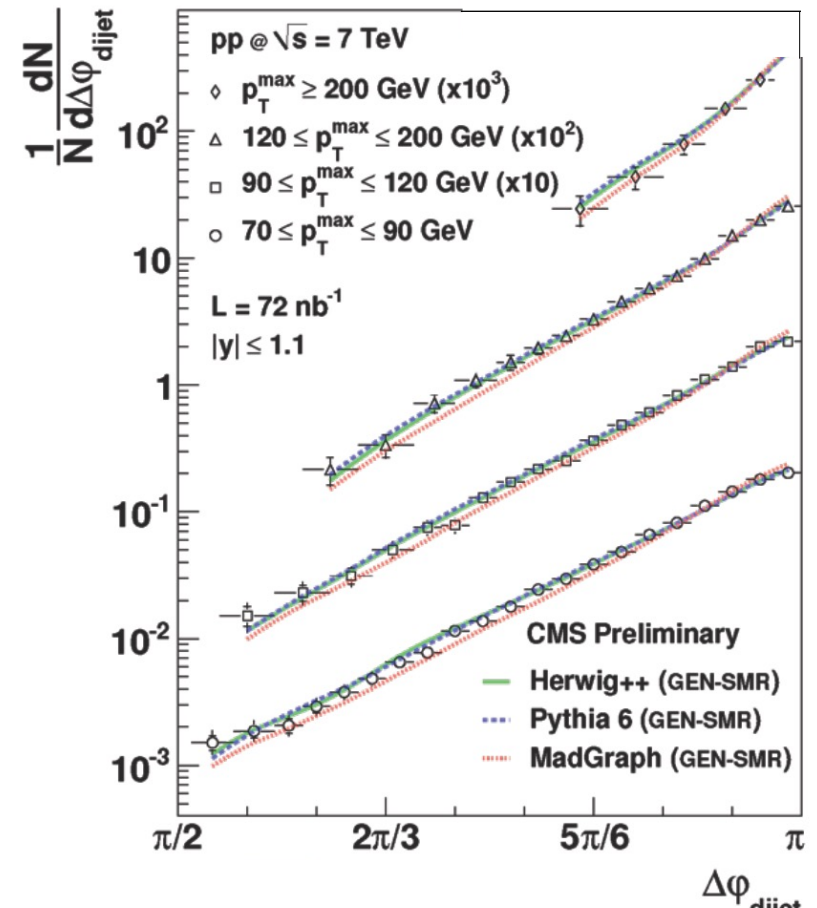
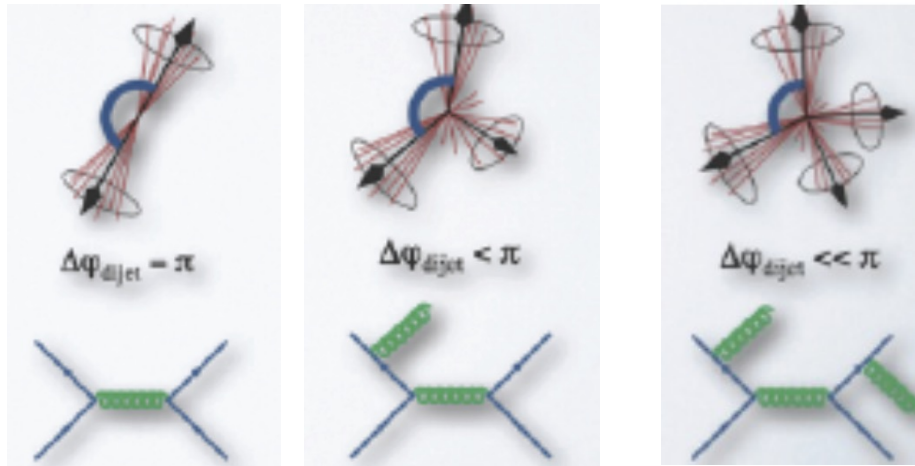
Jets: angular correlations

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

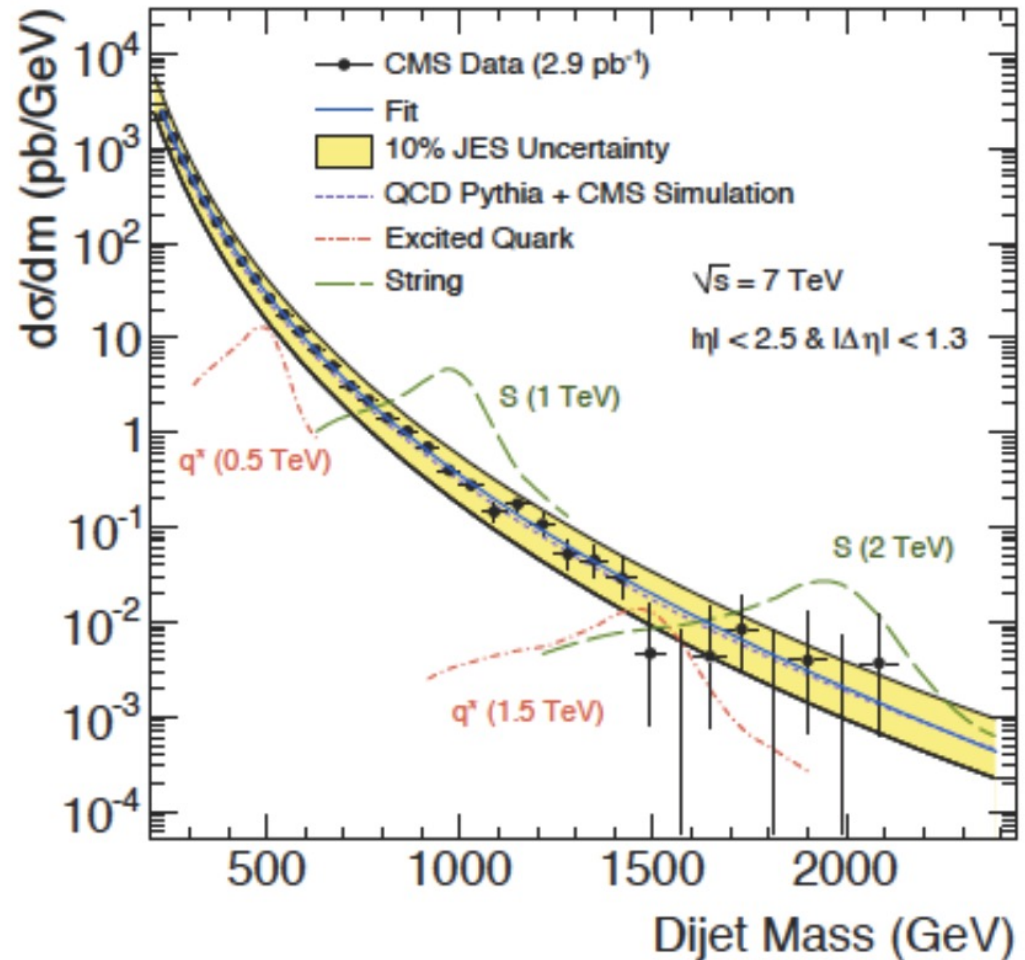
Search for numerous resonances
BSM:

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

Four-parameter fit to describe
QCD shape:

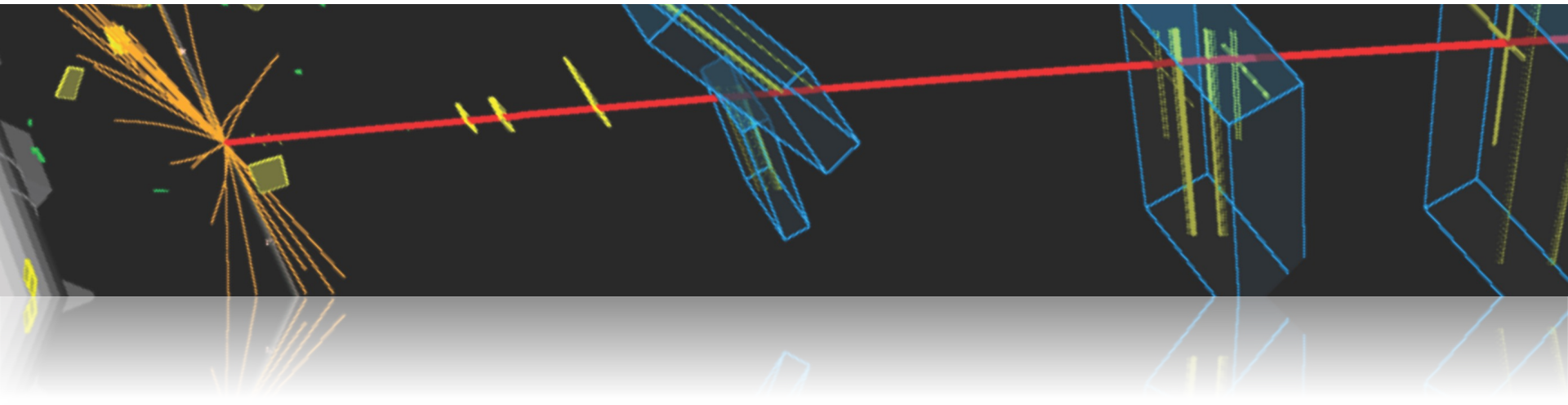
$$\frac{d\sigma}{dm} = p_0 \frac{\left(1 - \frac{m}{\sqrt{s}}\right)^{p_1}}{\left(\frac{m}{\sqrt{s}}\right)^B};$$

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



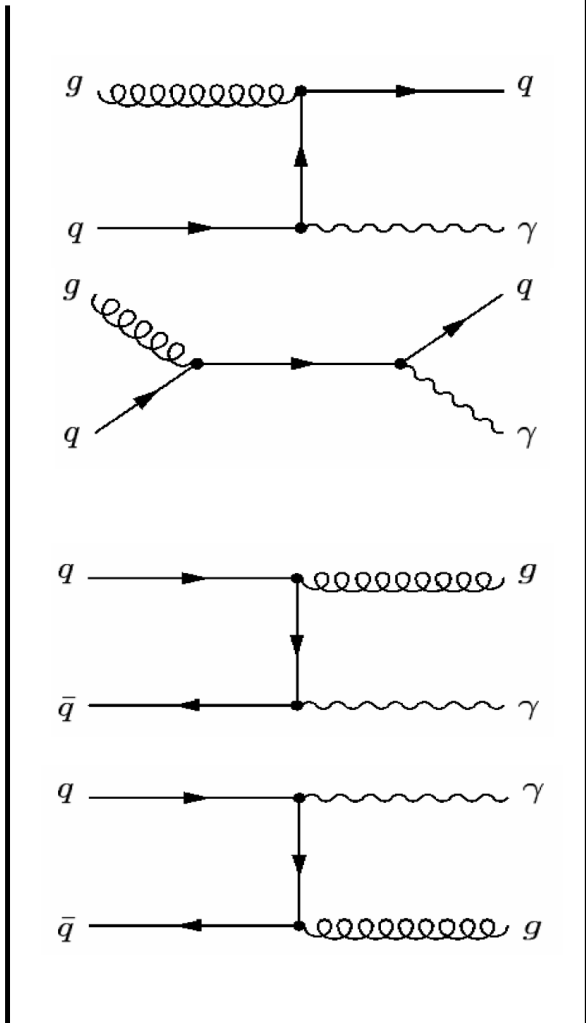
End of Lecture 2

W and Z bosons

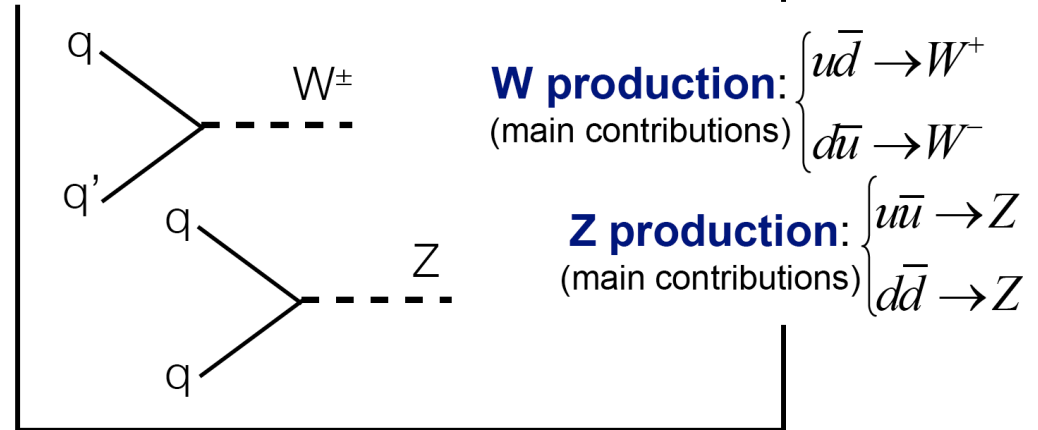


Vector boson production

Direct γ -production:



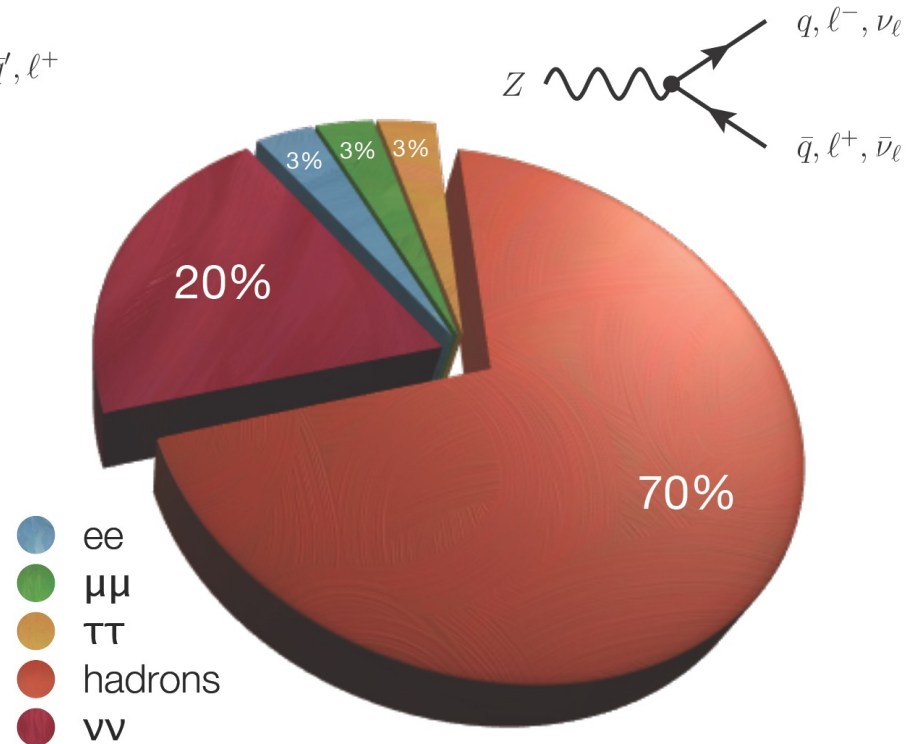
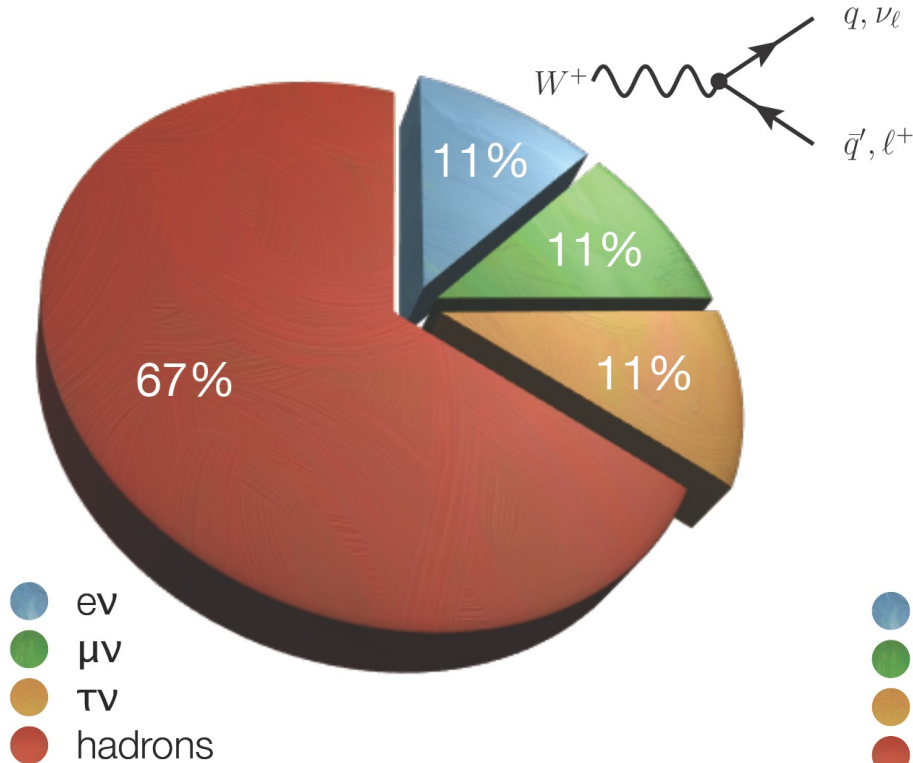
Singlet W/Z production:



- 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/μ): very clean, but small(ish) branching fractions

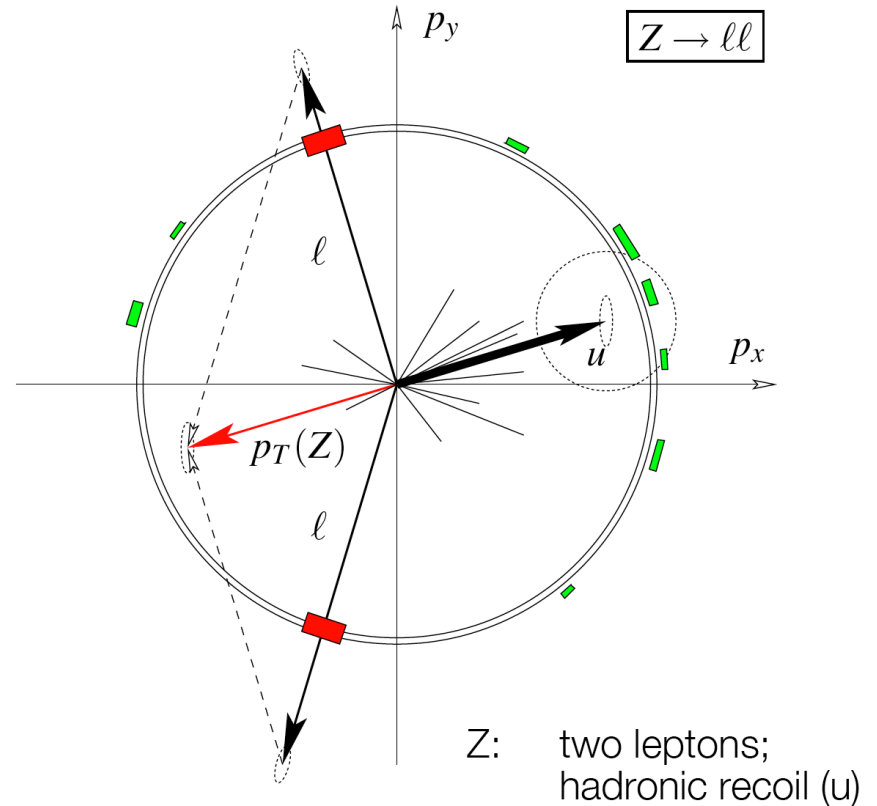
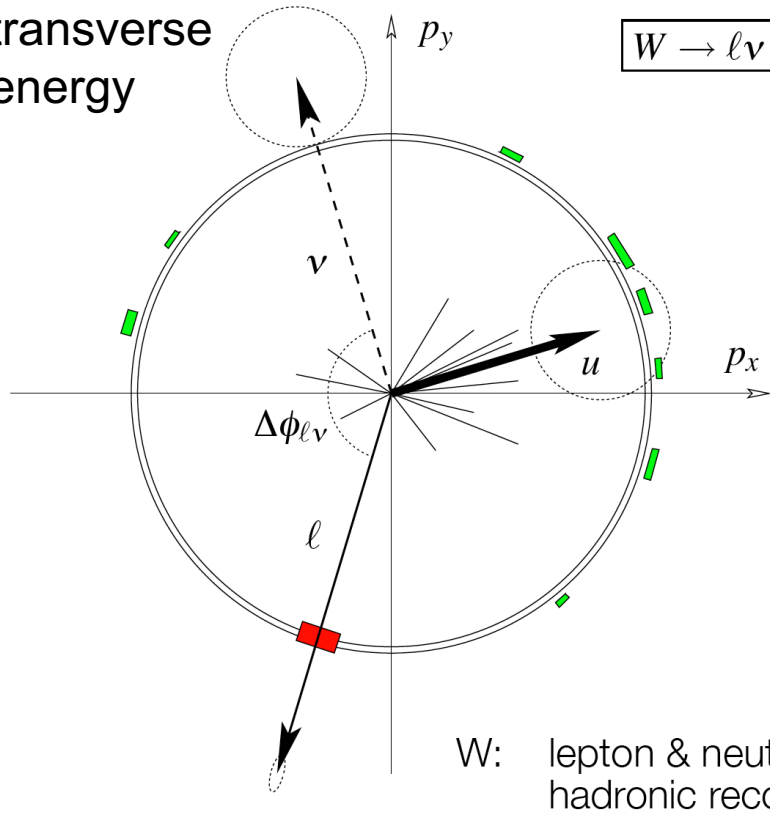
Hadronic decays: two-jet final states; large QCD dijet background

Tau decays: somewhere in between...

W and Z boson signatures

[CERN-OPEN-2008-020]

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 [$B \rightarrow l\nu X$]

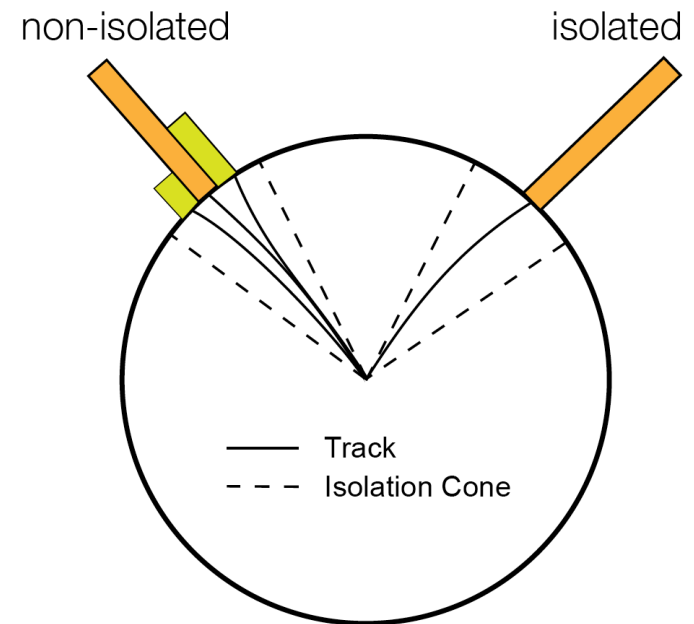
\rightarrow soft and surrounded by other particles

“Tight” lepton selection ...

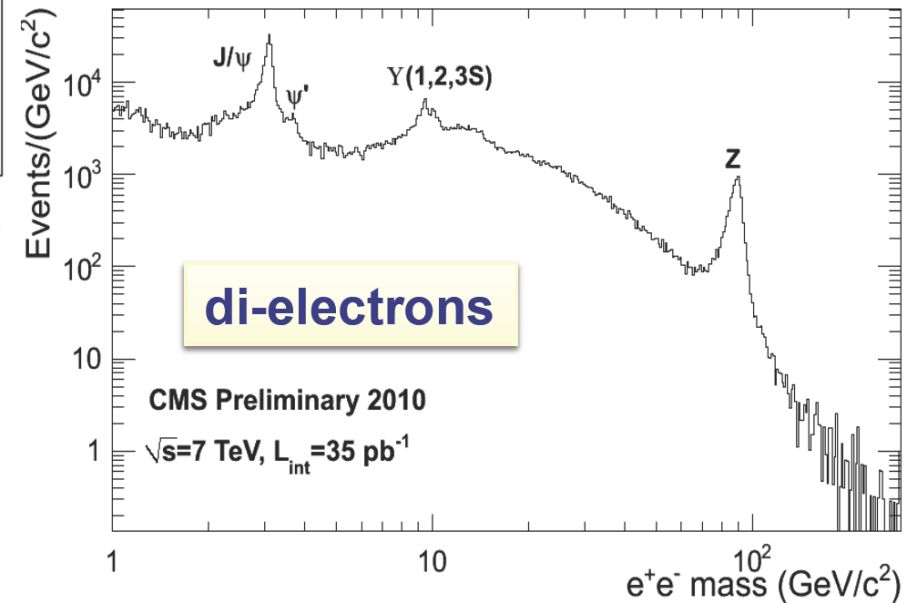
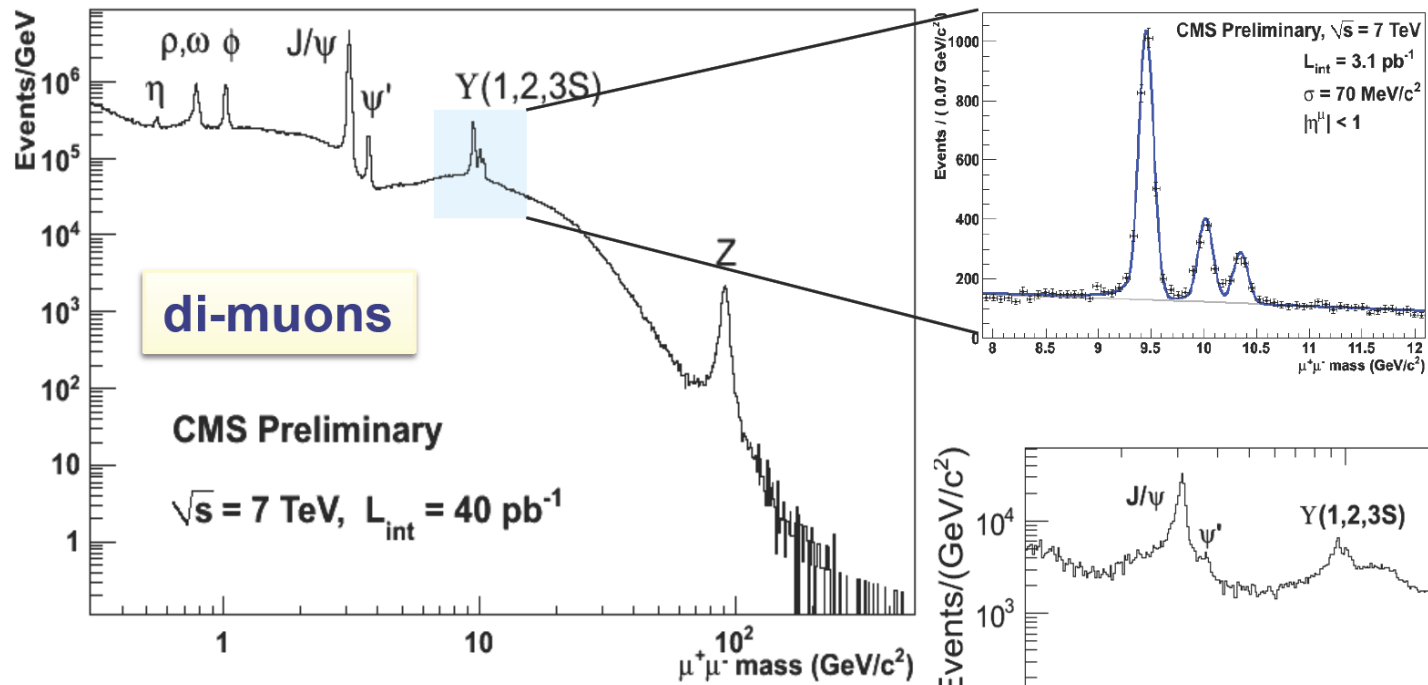
Require e/μ with $p_T > \text{(at least) } 20 \text{ GeV}$

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 $\Delta R=0.2$ less than 10%



Dilepton mass spectrum at 7 TeV



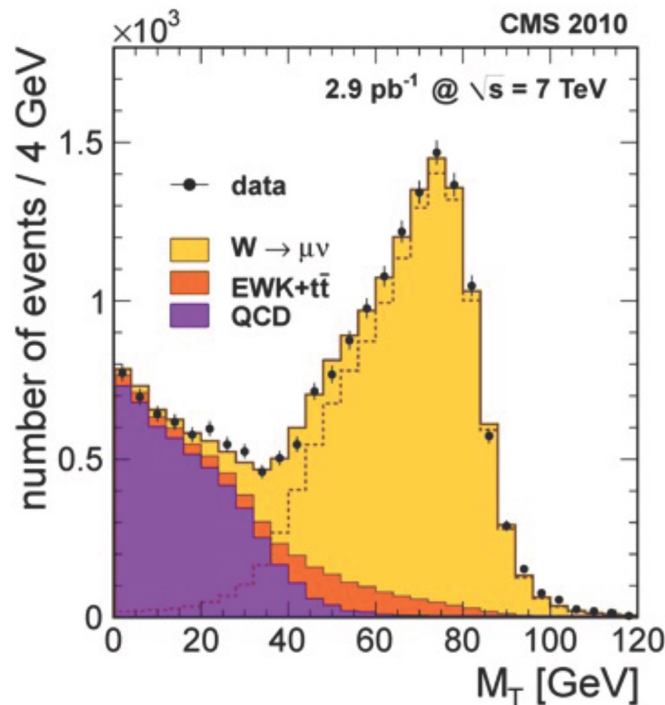
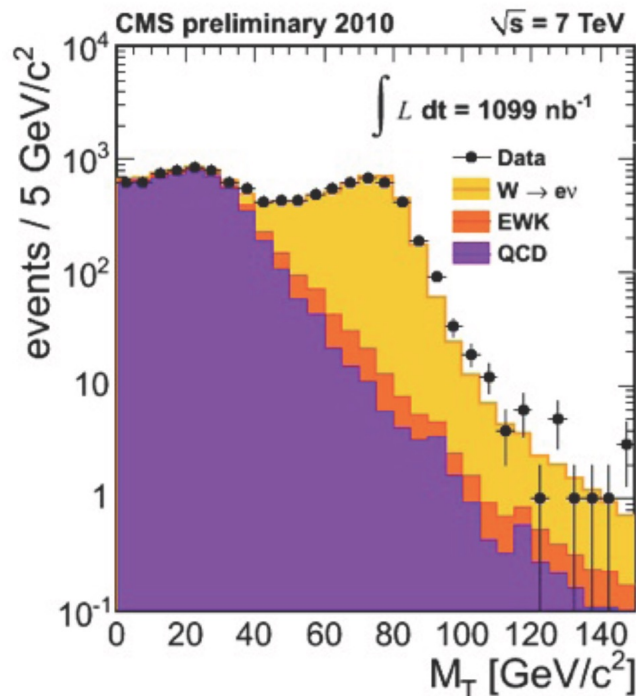
Example: CMS W Analysis

Select isolated electrons and muons ...

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

Investigate transverse mass ...

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

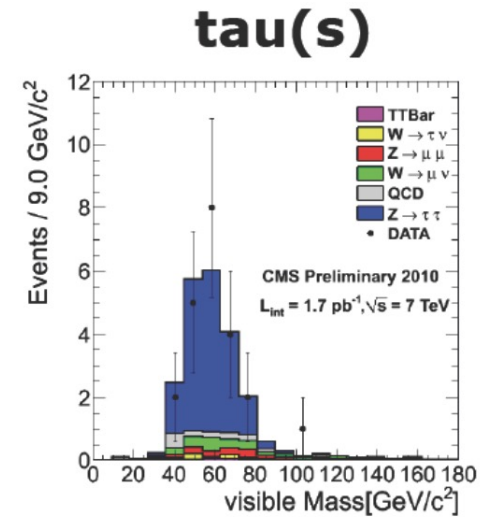
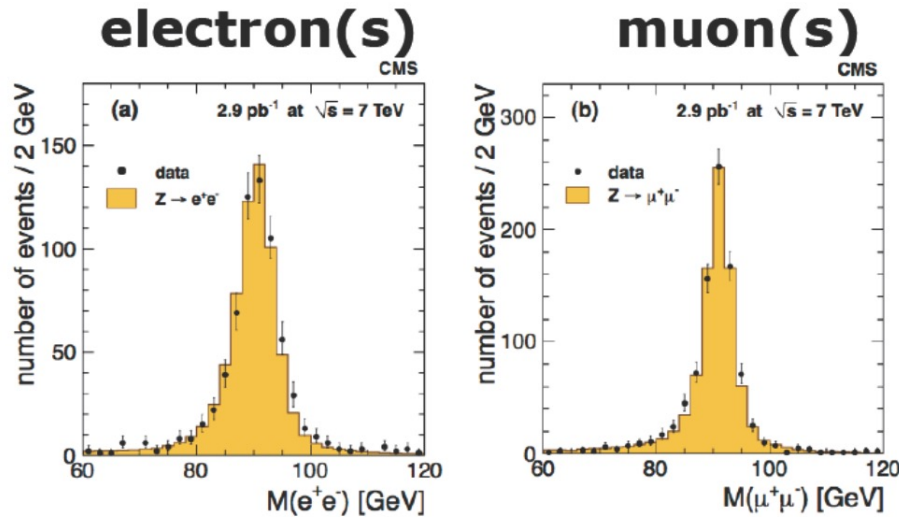


The W signal yield is extracted from a binned likelihood fit to the M_T distribution. Three different contributions:

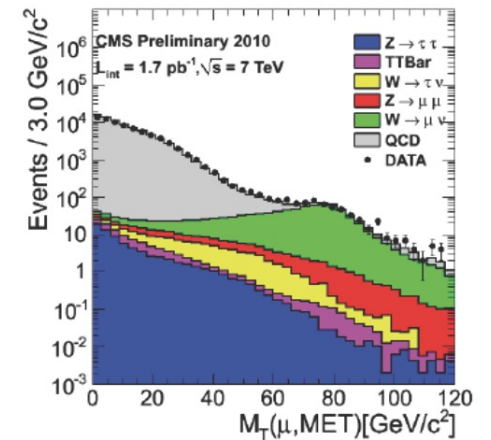
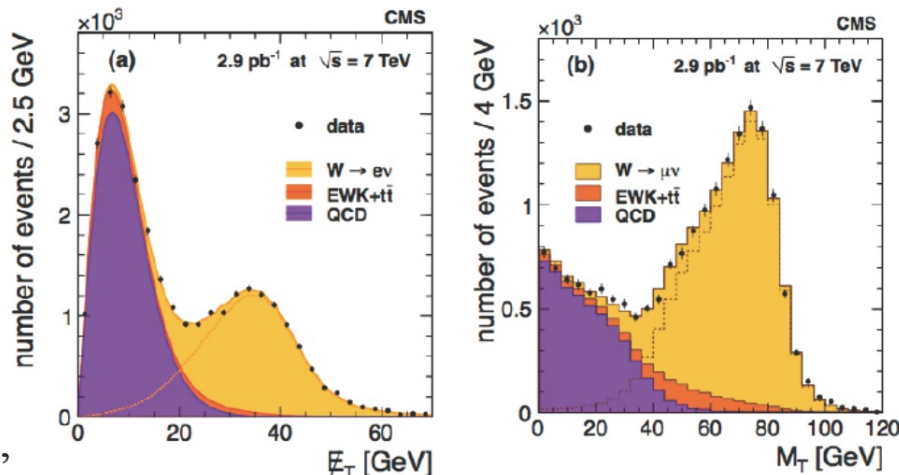
- W signal
- QCD background
- other (EWK) backgrounds.

W/Z production at 7 TeV

Z Boson



W Boson

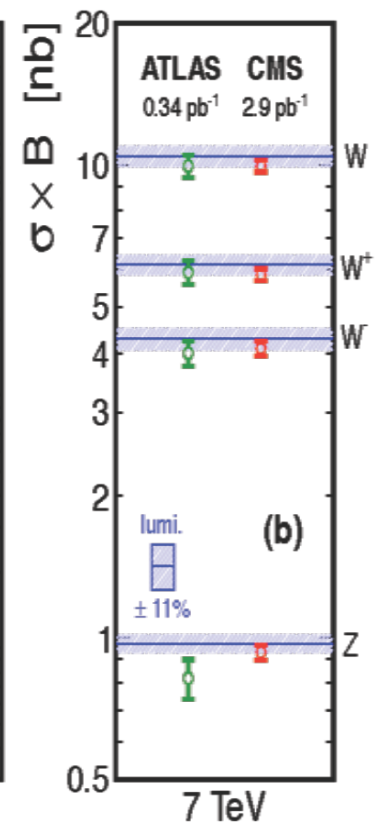
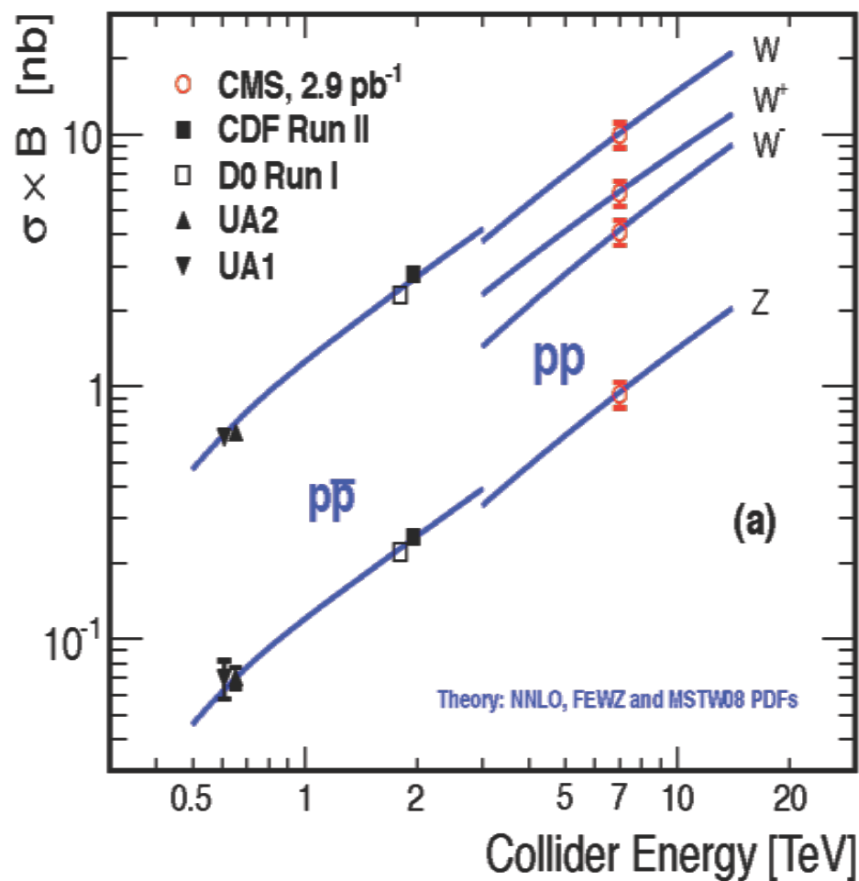
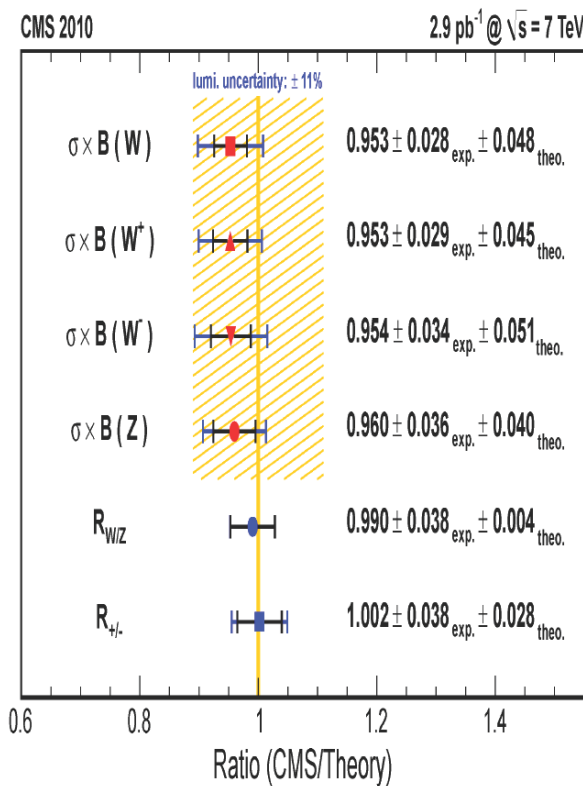


Transverse Mass,

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

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]

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

Proton-Proton Collider:

symmetry around $y=0$...

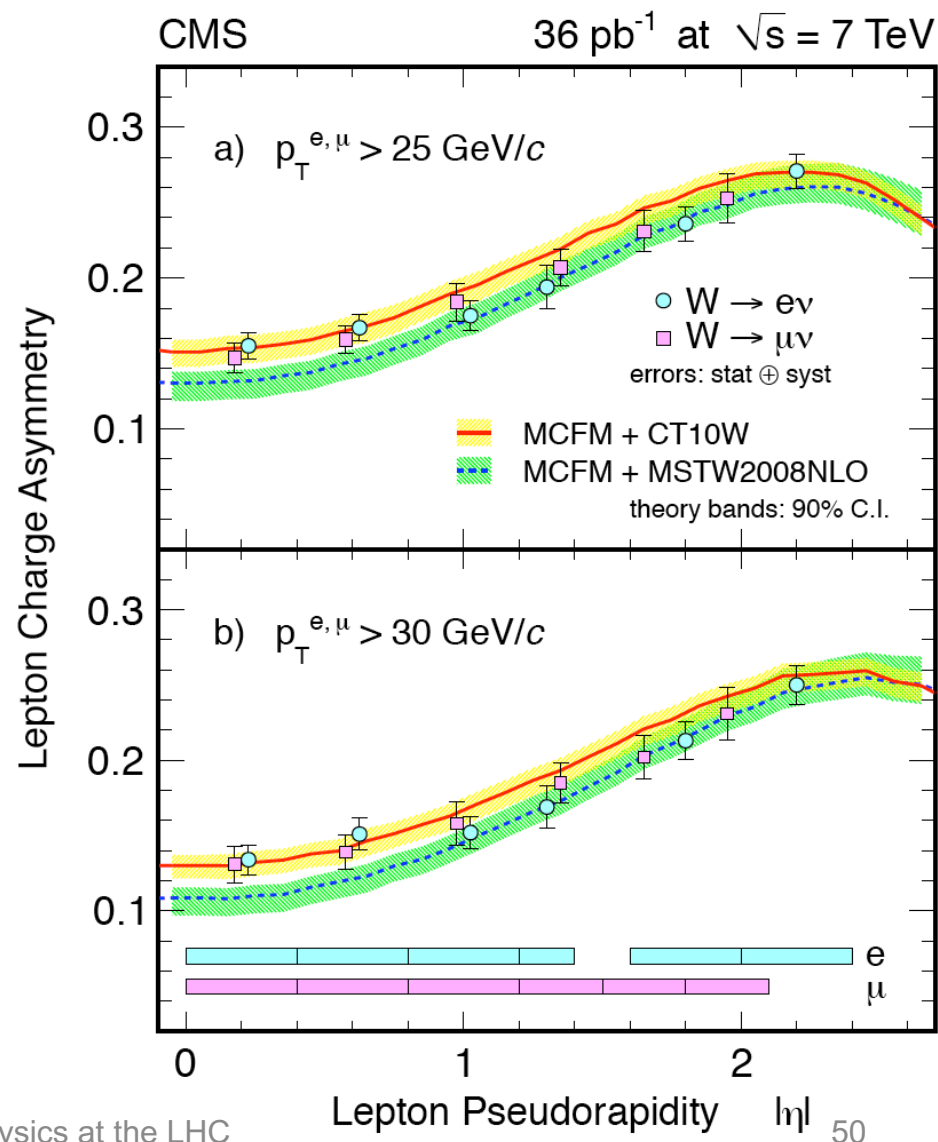
PDFs:

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

more W⁺ at positive rapidity

d/u ratio < 1 ...

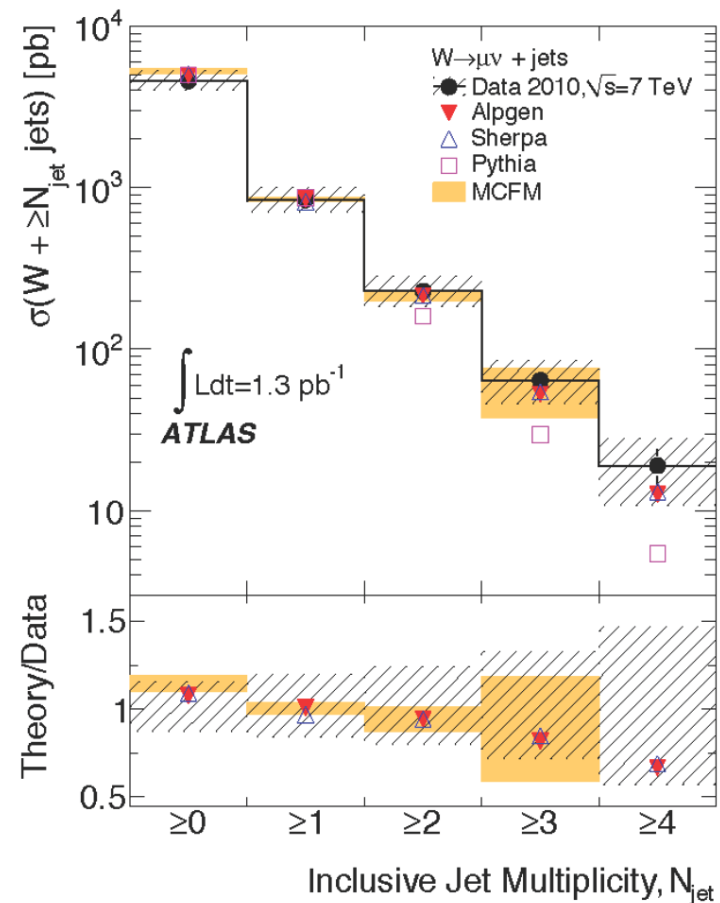
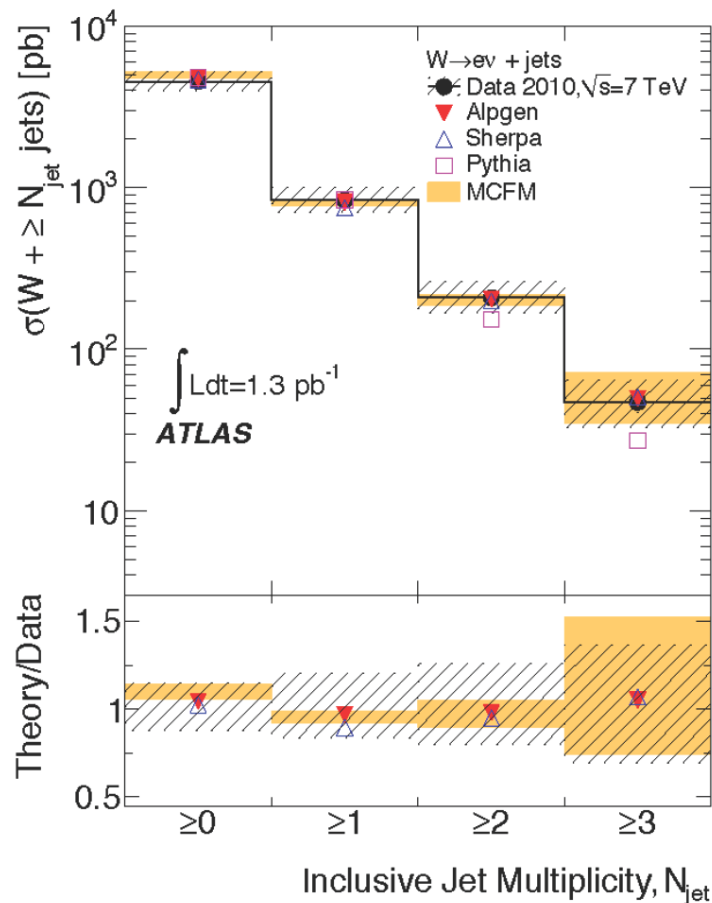
always more W⁺ than W⁻



W + Jets multiplicity

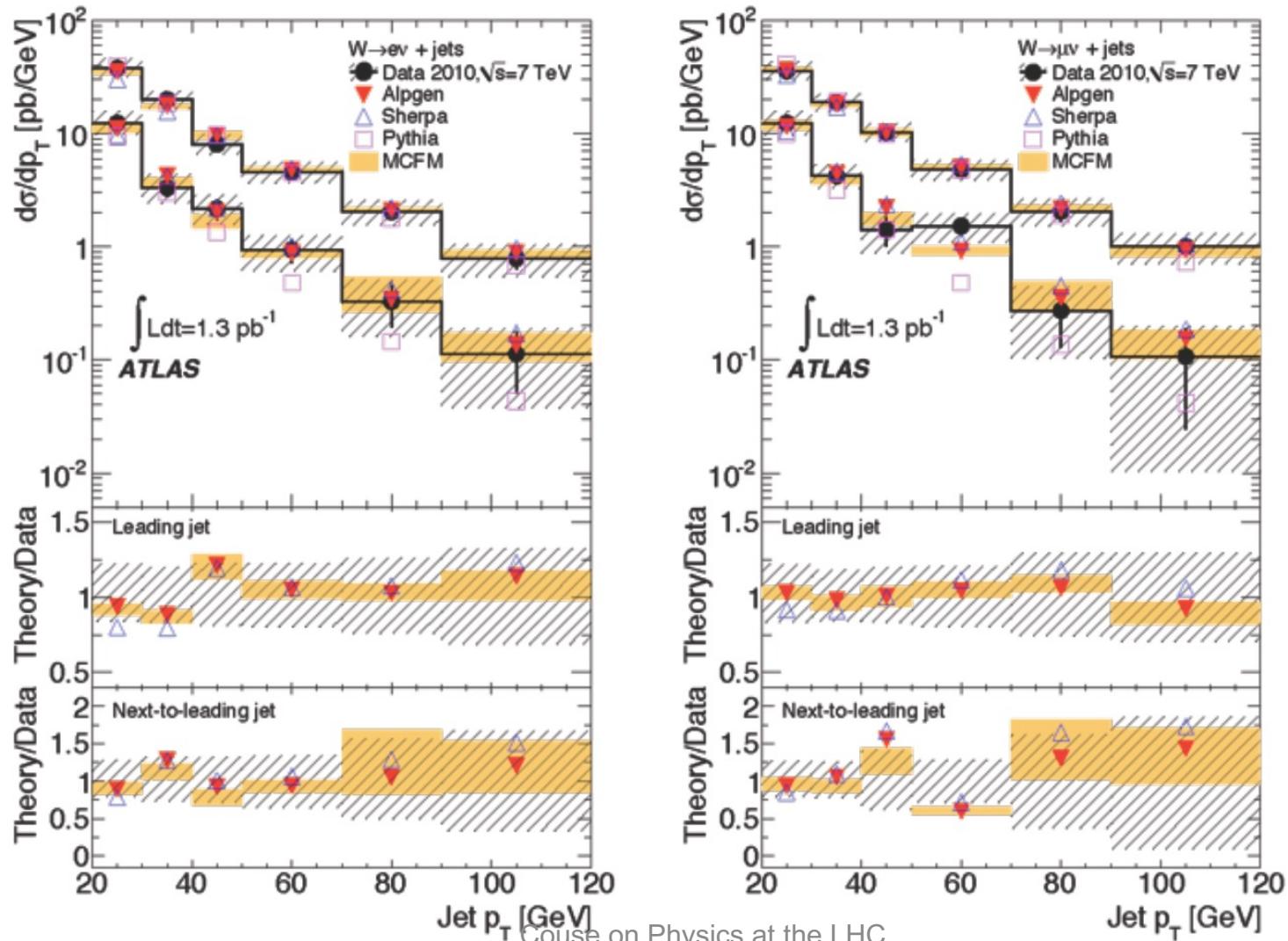
$|\eta| < 2.8$ and $p_T > 20$ GeV

arXiv:1012.5382

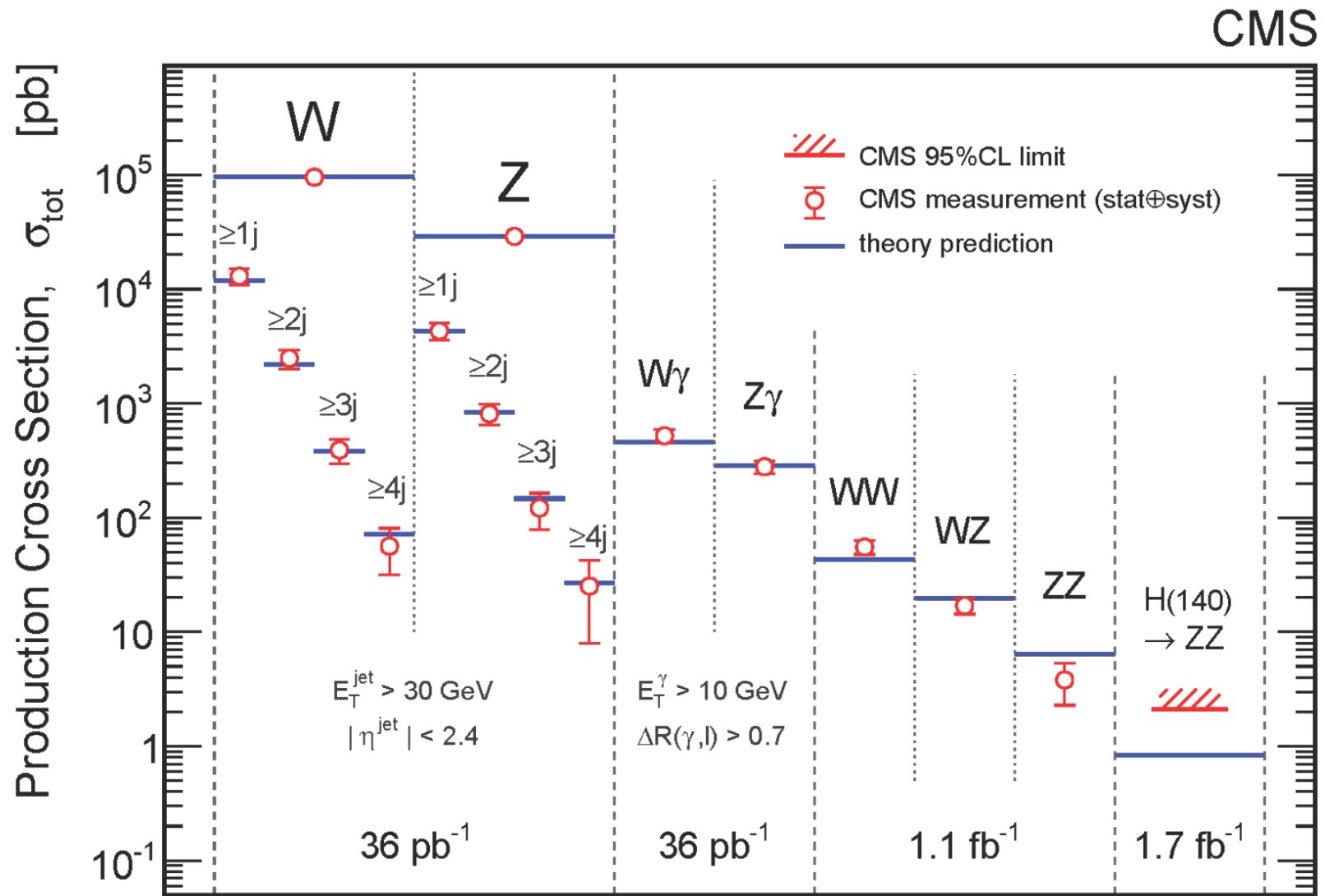


W + Jets P_T

Tails are important in several Exotica and SUSY searches



SM processes measured at LHC



W Mass Determination

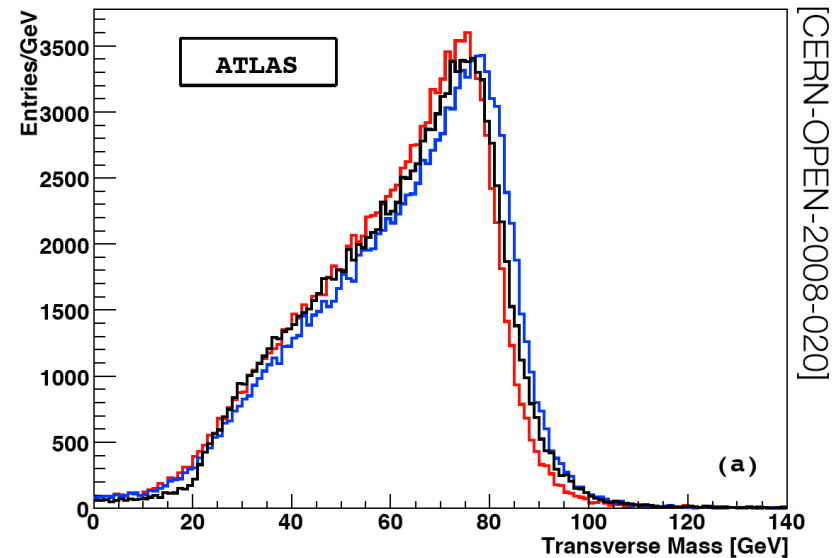
Template method:

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]