Karlsruher Institut für Technologie

Particle Physics at the LHC

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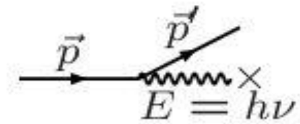
KIT Center Elementary Particle and Astroparticle Physics - KCETA

Subjects to discuss:

- Hadron collider basics
- Cross section formula and collider kinematics
- Higgs physics at the LHC
  - Review of SM and MSSM Higgs sector
  - Higgs boson production and decay
  - Signals at the LHC
  - Measurement of Higgs couplings
  - BSM effects and effective Lagrangians
- NLO effects
- Beyond fixed order perturbation theory: parton shower
- Merging of NLO and parton showers

Hadron collider basics

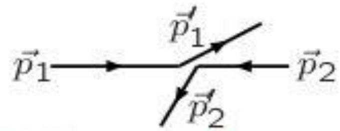
To study the deepest layers of matter,
we need the probes with highest energies.



$p = h/\lambda$

Two parameters of importance:

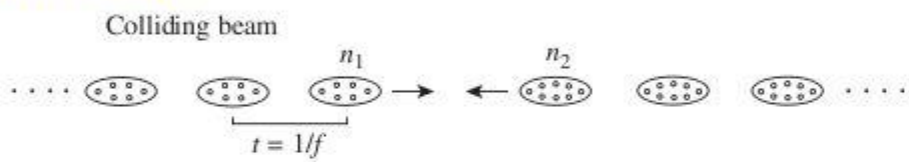
1. The energy:



$$s \equiv (p_1 + p_2)^2 = \begin{cases} (E_1 + E_2)^2 & \text{in the c.m. frame } \vec{p}_1 + \vec{p}_2 = 0, \\ m_1^2 + m_2^2 + 2(E_1 E_2 - \vec{p}_1 \cdot \vec{p}_2). & \end{cases}$$

$$E_{cm} \equiv \sqrt{s} \approx \begin{cases} 2E_1 \approx 2E_2 & \text{in the c.m. frame } \vec{p}_1 + \vec{p}_2 = 0, \\ \sqrt{2E_1 m_2} & \text{in the fixed target frame } \vec{p}_2 = 0. \end{cases}$$

2. The luminosity:



$$\mathcal{L} \propto f n_1 n_2 / a,$$

(a some beam transverse profile) in units of #particles/cm^2/s
$\Rightarrow 10^{33}$ cm^{-2}s^{-1} $= 1$ nb^{-1} s^{-1} ≈ 10 fb^{-1}/year.

Tevatron and LHC

LHC precursor: Tevatron, $p\bar{p}$ collisions at
$\sqrt{s} = 1.96$ TeV $\quad \mathcal{L} \approx 2 - 3 \times 10^{32}$ cm^{-2}sec$^{-1} \leftrightarrow 2 - 3$fb^{-1}/year

LHC, designed for pp collisions at
$\sqrt{s} = 14$ TeV $\quad \mathcal{L} \approx 10^{33}$–$10^{34}$ cm^{-2}sec$^{-1} \leftrightarrow 10$–100fb^{-1}/year
lower energy and luminosity at beginning:
$\sqrt{s} = 7 + 8$ TeV and $\quad \int \mathcal{L}dt \approx 5 + 20$ fb^{-1} in 2011/12 $\quad$ Run I
$\sqrt{s} = 13$ TeV and $\quad \int \mathcal{L}dt \approx 2.5$ fb^{-1} in 2015 $\quad$ Beginning of Run II

Advantage: available energy is much larger than at e^+e^- colliders

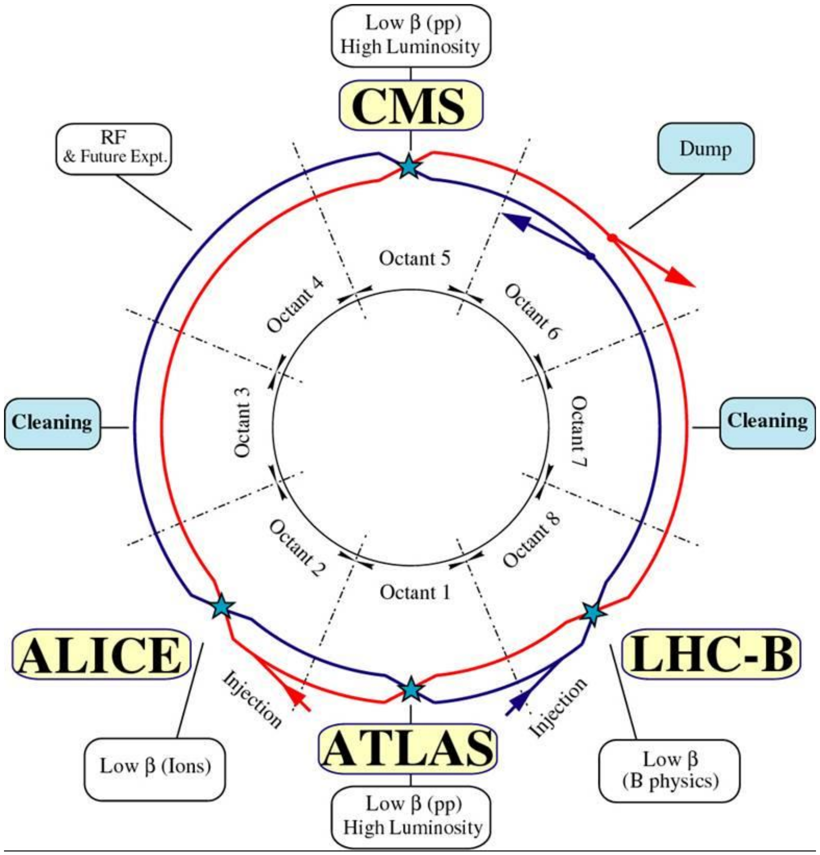
- $t\bar{t}$ pairs could not be produced at LEP...

Disadvantage: protons are composite $\Longrightarrow$

- hard scattering is between
  partons = quarks, anti-quarks, gluons
- useful energy = $\sqrt{\hat{s}}$ of partons $<< \sqrt{s}$
- proton-(anti)proton cross section is large
  $\sigma_{tot}(p\bar{p}) \approx 100$ mb $\geq 10^{11}$ times new physics cross sections
  $\Longrightarrow$ Must understand patterns of SM and new physics processes to identify something new

The LHC is housed about 100 m underground in a 27 km circumference tunnel straddling the French-Swiss border

Experiments at the LHC



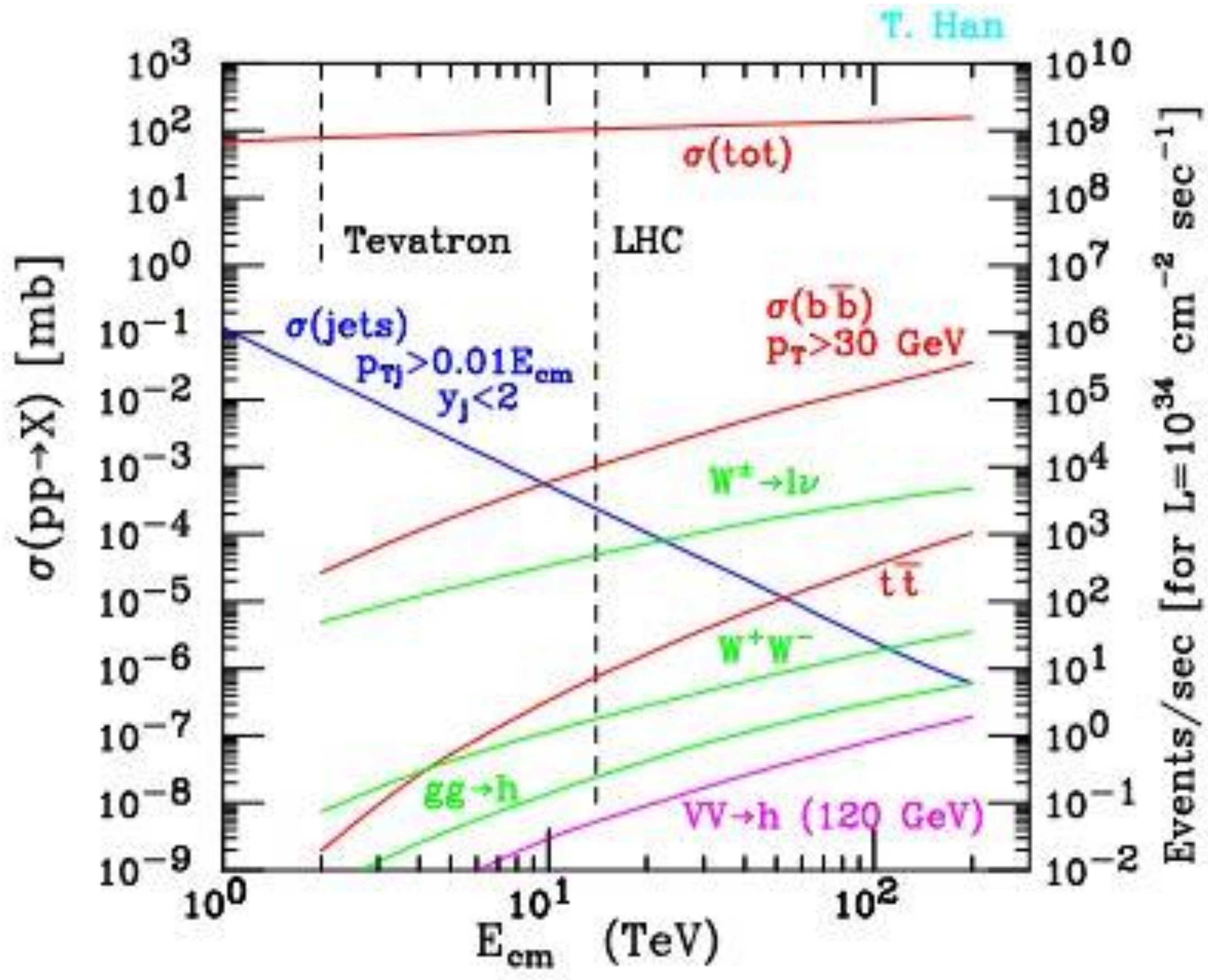
Collisions take place in four experiments

- ATLAS and CMS are general purpose detectors aiming at study of all hard interactions
- LHCb looks for B-mesons and baryons produced in the forward direction
- ALICE is a detector designed for the extremely high particle numbers produced in heavy ion collisions

What to look for at the LHC?

- Jet production = elastic parton-parton scattering
- Top Quarks
- Electroweak gauge bosons: W and Z
- Higgs production and decay
- Evidence for beyond the SM physics
  - Supersymmetry
  - non-standard electroweak interactions
  - extra gauge bosons
  - ….. the unexpected

Expected cross sections in pp collisions



Detecting hadrons, leptons and photons

What we "see" as particles in the detector: (a few meters)

For a relativistic particle, the travel distance:

$$d = (\beta c \tau)\gamma \approx (300\ \mu m)(\frac{\tau}{10^{-12}\ s})\ \gamma$$

- stable particles directly "seen":

$$p,\ \bar{p},\ e^{\pm},\ \gamma$$

- quasi-stable particles of a life-time $\tau \geq 10^{-10}$ s also directly "seen":

$$n, \Lambda, K^0_L, ...,\ \mu^{\pm},\ \pi^{\pm}, K^{\pm}...$$

- a life-time $\tau \sim 10^{-12}$ s may display a secondary decay vertex, "vertex-tagged particles":

$$B^{0,\pm},\ D^{0,\pm},\ \tau^{\pm}...$$

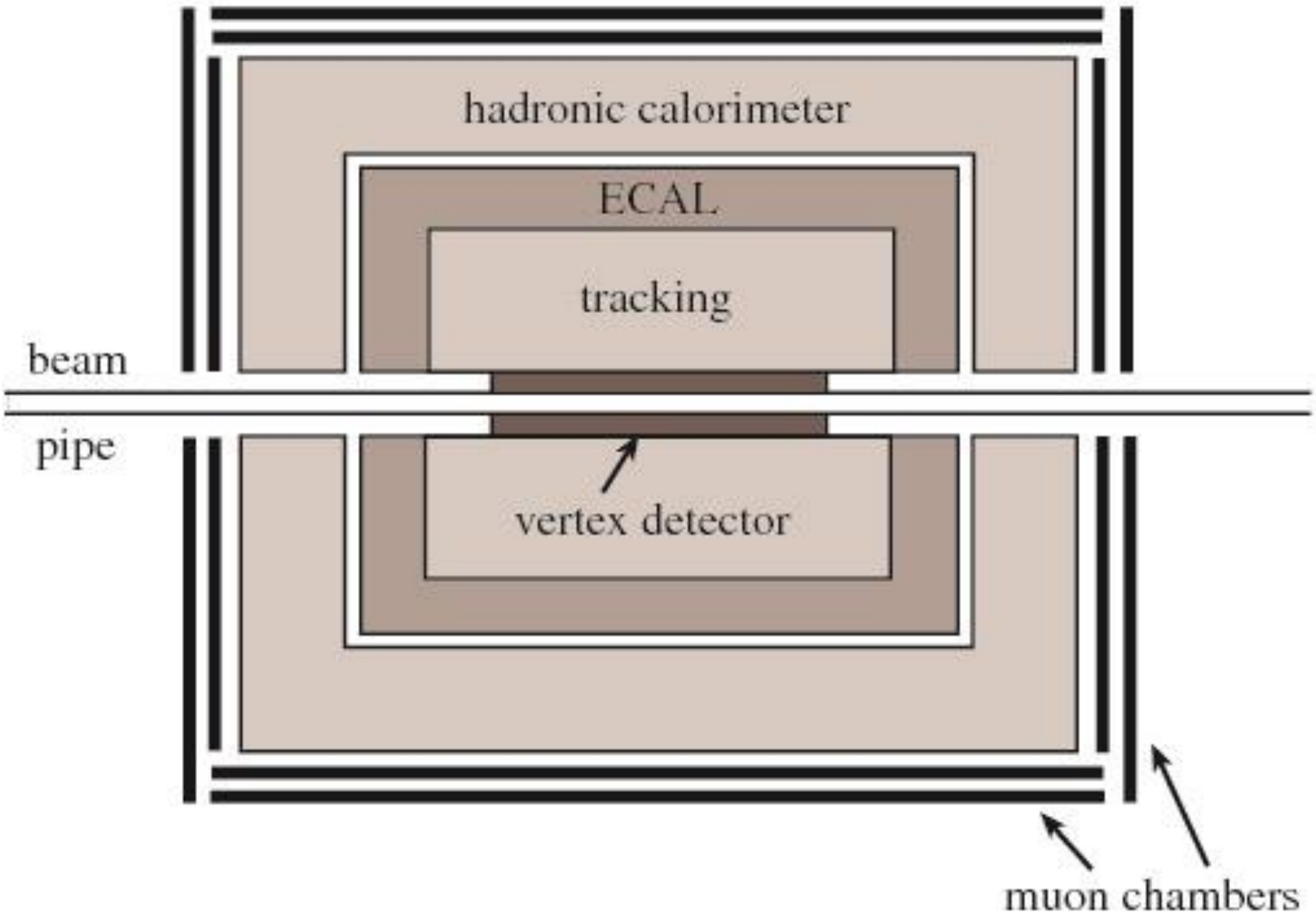
- short-lived not "directly seen", but "reconstructable":

$$\pi^0,\ \rho^{0,\pm}...\ ,\ \ Z, W^{\pm}, t, H...$$

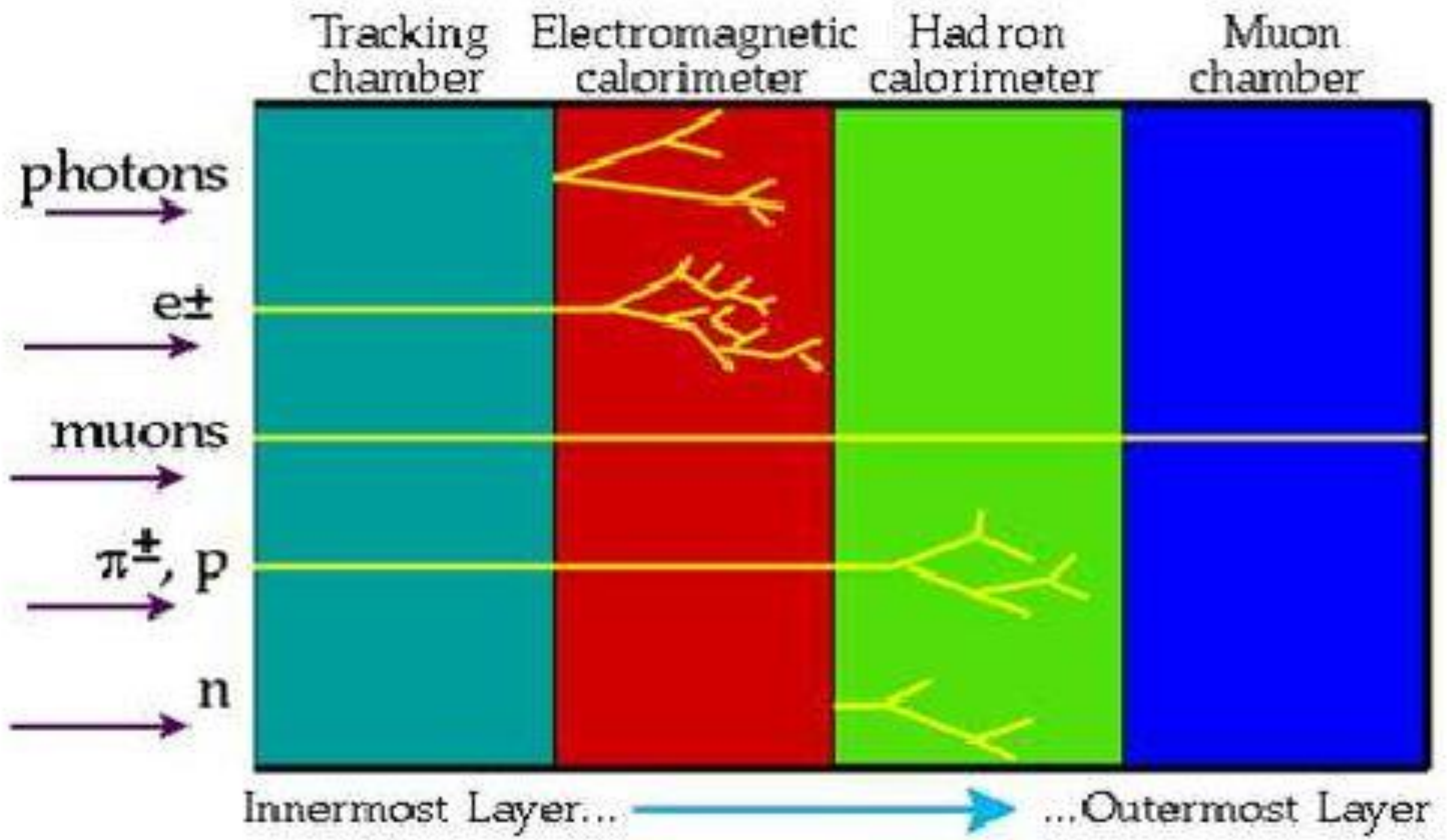
- missing particles are weakly-interacting and neutral:

$$\nu,\ \tilde{\chi}^0, G_{KK}...$$

Basic concept of a general purpose detector



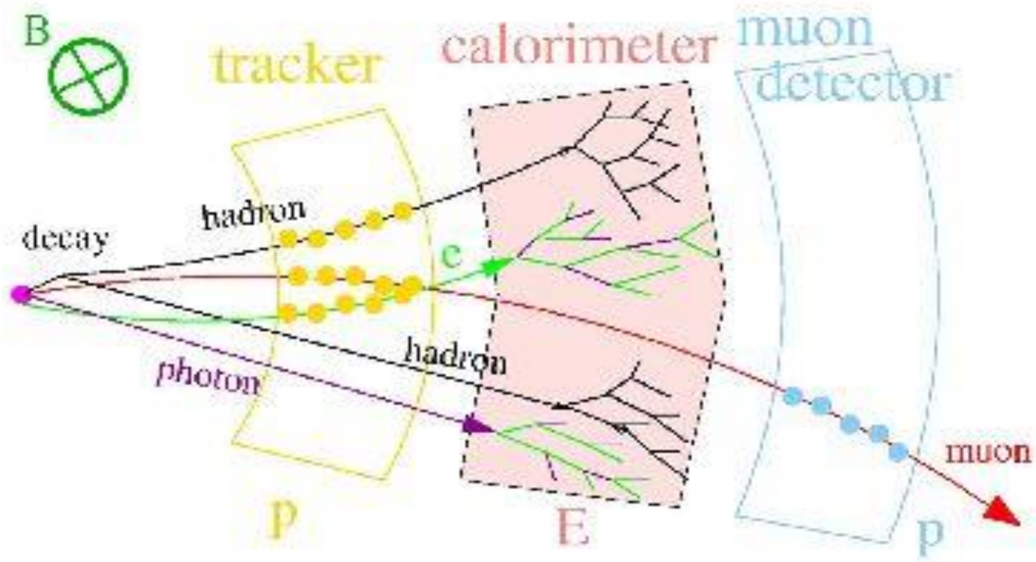
† For stable and quasi-stable particles of a life-time $\tau \geq 10^{-10} - 10^{-12}$ s, they show up as



For details see lectures by N.K.Mondal

Charge identification and momentum resolution

A closer look:



Theorists should know:

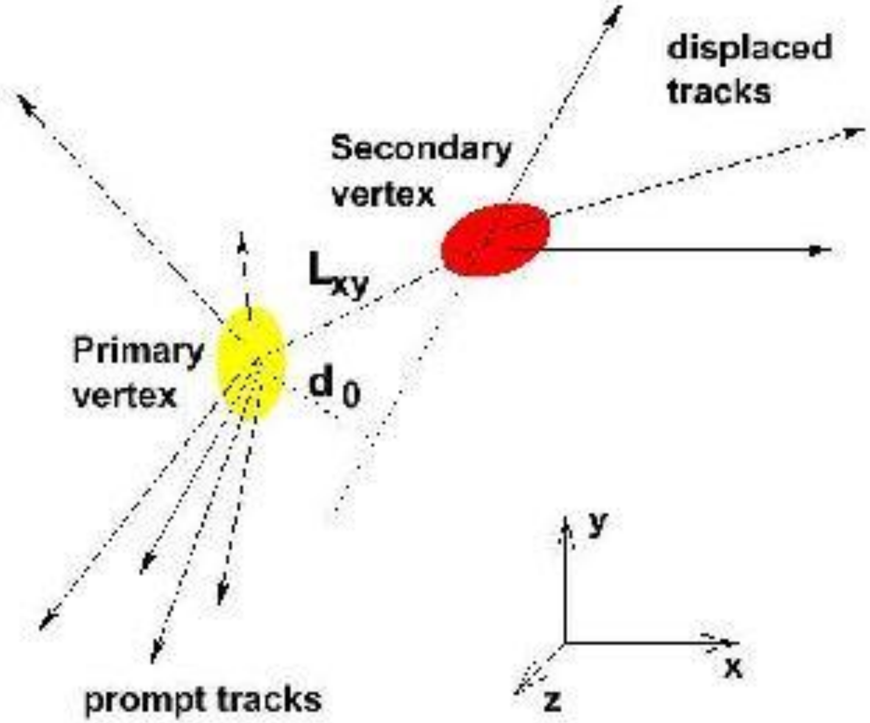
For charged tracks : $\Delta p/p \;\propto\; p,$

typical resolution : $\sim\; p/(10^4\; GeV).$

For calorimetry : $\Delta E/E \;\propto\; \frac{1}{\sqrt{E}},$

typical resolution : $\sim\; (5-80\%)/\sqrt{E}.$

† For vertex-tagged particles $\tau \approx 10^{-12}$ s,
heavy flavor tagging: the secondary vertex:



Typical resolution: $d_0 \sim 30 - 50\ \mu$m or so

$\Rightarrow$ need at least two charged tracks, that are not colinear.

For theorists: just multiply a "tagging efficiency" $\epsilon_b \sim 40 - 60\%$ or so.

Short lived and „invisible“ particles:

† For short-lived particles: $\tau < 10^{-12}$ s or so,

make use of kinematics to reconstruct the resonance.

† For missing particles:

make use of energy-momentum conservation to deduce their existence.

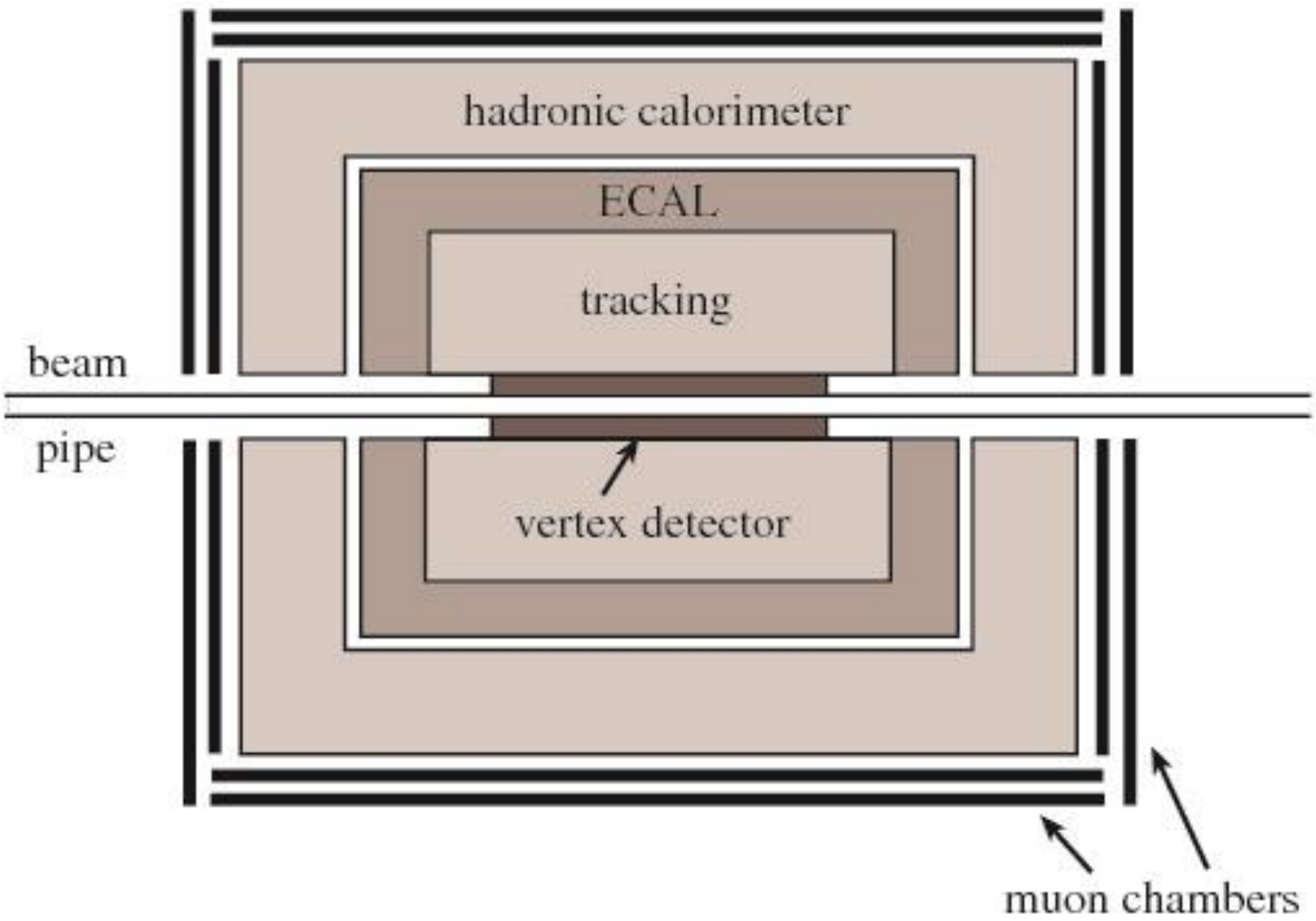
(or transverse direction only for hadron colliders.)

$$p_1^i + p_2^i = \sum_f^{obs.} p_f + p_{miss}.$$

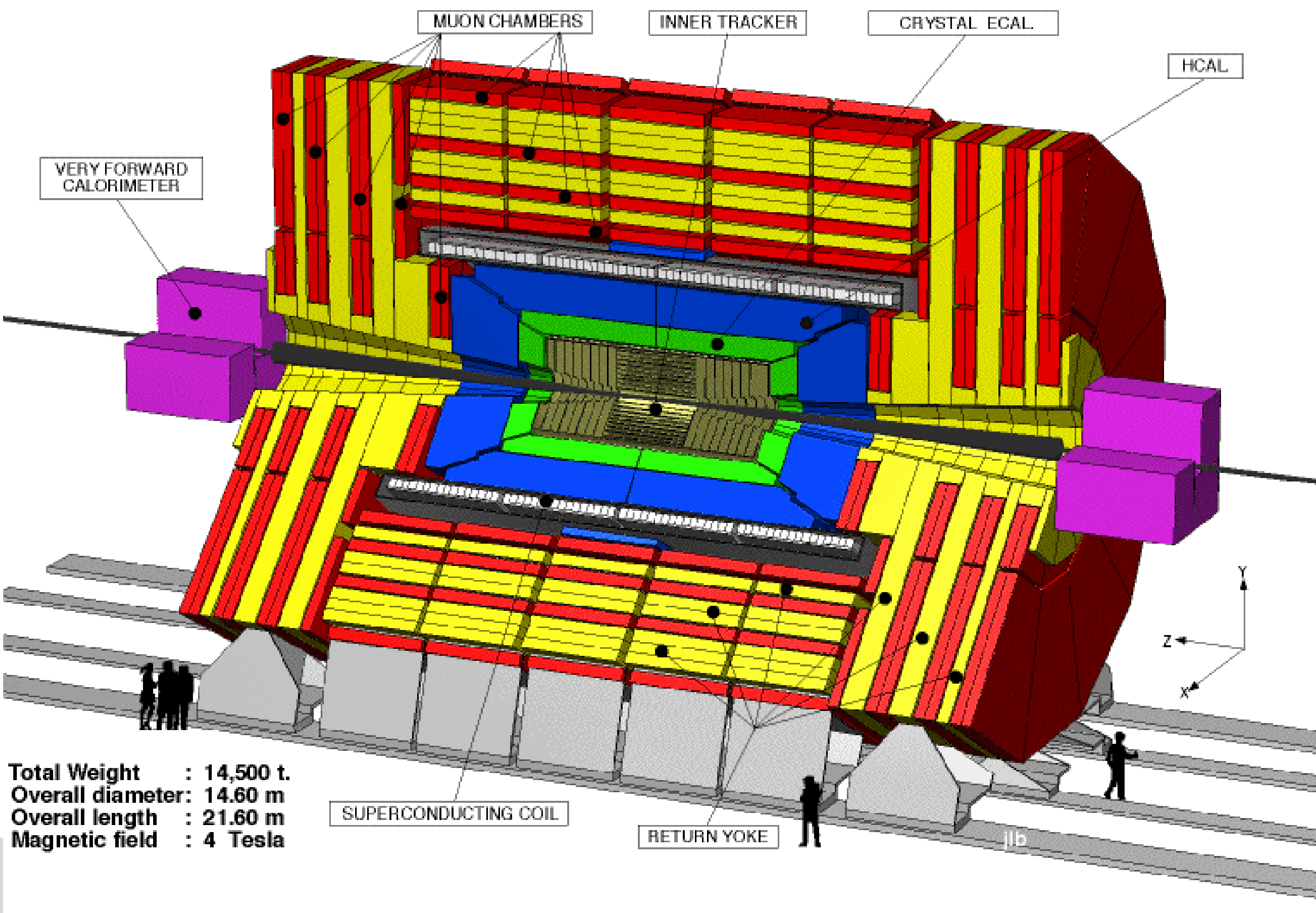
But in hadron collisions, the longitudinal momenta unkown:

$$0 = \sum_f^{obs.} \vec{p}_{f\ T} + \vec{p}_{miss\ T}.$$

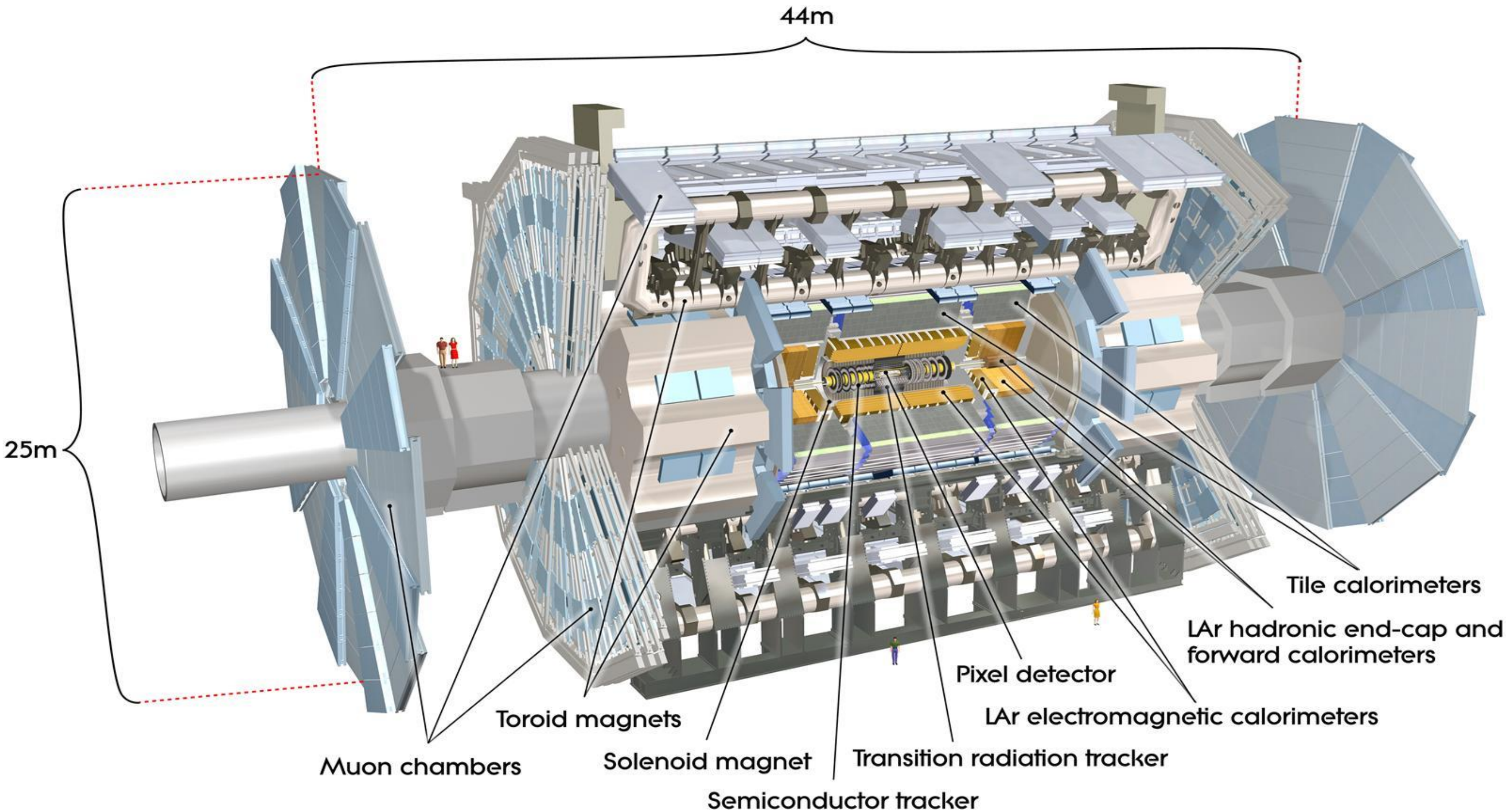
Cartoon of a general purpose detector



Layout of the CMS detector



Components of the ATLAS detector



Cross sections for hadronic collisions

Parton distribution functions

Factorization Theorem for infrared and collinear safe observable i.e. observables which are insensitive to soft gluon emission or collinear splitting

Any infrared and collinear safe observable (depending on hard internal momenta Q) in the scattering of two hadrons h_1 and h_2 can be expressed as a convolution of parton distribution functions $f_{a/h}(x,\mu_f)$ with hard scattering kernels H_{ab}

$$\begin{aligned} H &= \sum_{a,b} \int_0^1 dx_1 dx_2\, f_{a/h_1}(x_1,\mu_f)\, H_{ab}(Q; Q^2/\mu^2, \mu_f/\mu, \alpha_s(\mu))\, f_{b/h_2}(x_2,\mu_f) \\ &+ \text{terms of order} \frac{\Lambda^2_{QCD}}{Q^2} \end{aligned}$$

- The hard scattering kernel is calculable in perturbation theory and is independent of long distance effects, in particular it does not depend on the nature of the hadrons h_1 and h_2. Trick: consider the special case with $h_i =$ external partons
- The pdf's are universal in that they only depend on the nature of the hadron h_1, h_2 and the extracted parton a, b, but not on the details of the hard process.

PDF's continued

The physical observable H is independent of the factorization scale μ_f. Using the perturbative μ_f dependence of the H_{ab} one obtains evolution equations for the pdf's, the DGLAP equation

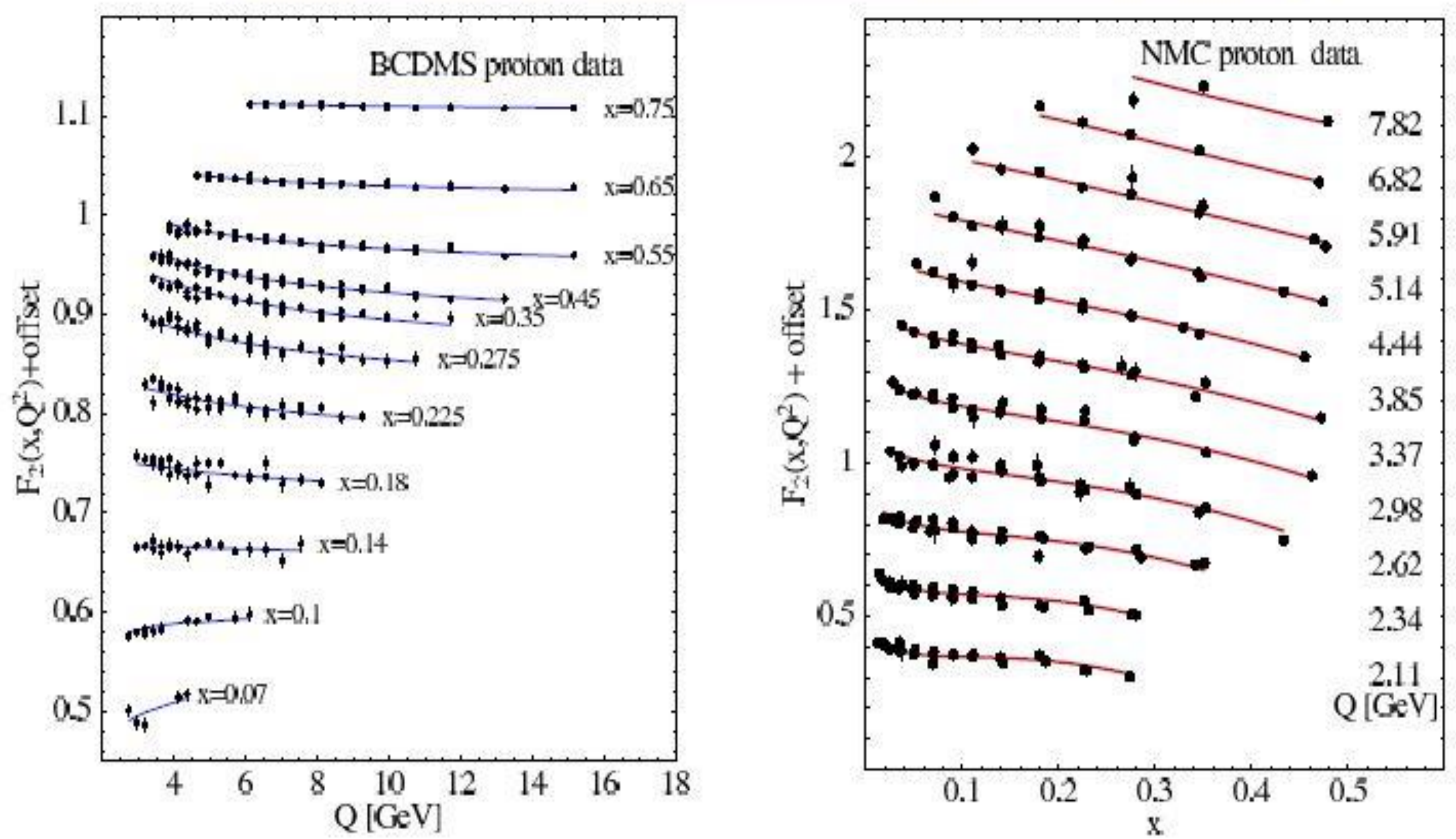
$$\mu \frac{d}{d\mu} f_{a/h}(x,\mu) = \sum_{j=q,\bar{q},g} \int_x^1 \frac{d\xi}{\xi} P_{ij}\left(\frac{x}{\xi}, \alpha_s(\mu)\right) f_{j/h}(\xi,\mu)$$

where the P_{ij} are exactly the Altarelli-Parisi evolution kernels

By combining information from many experiments, the pdf's are extracted from data

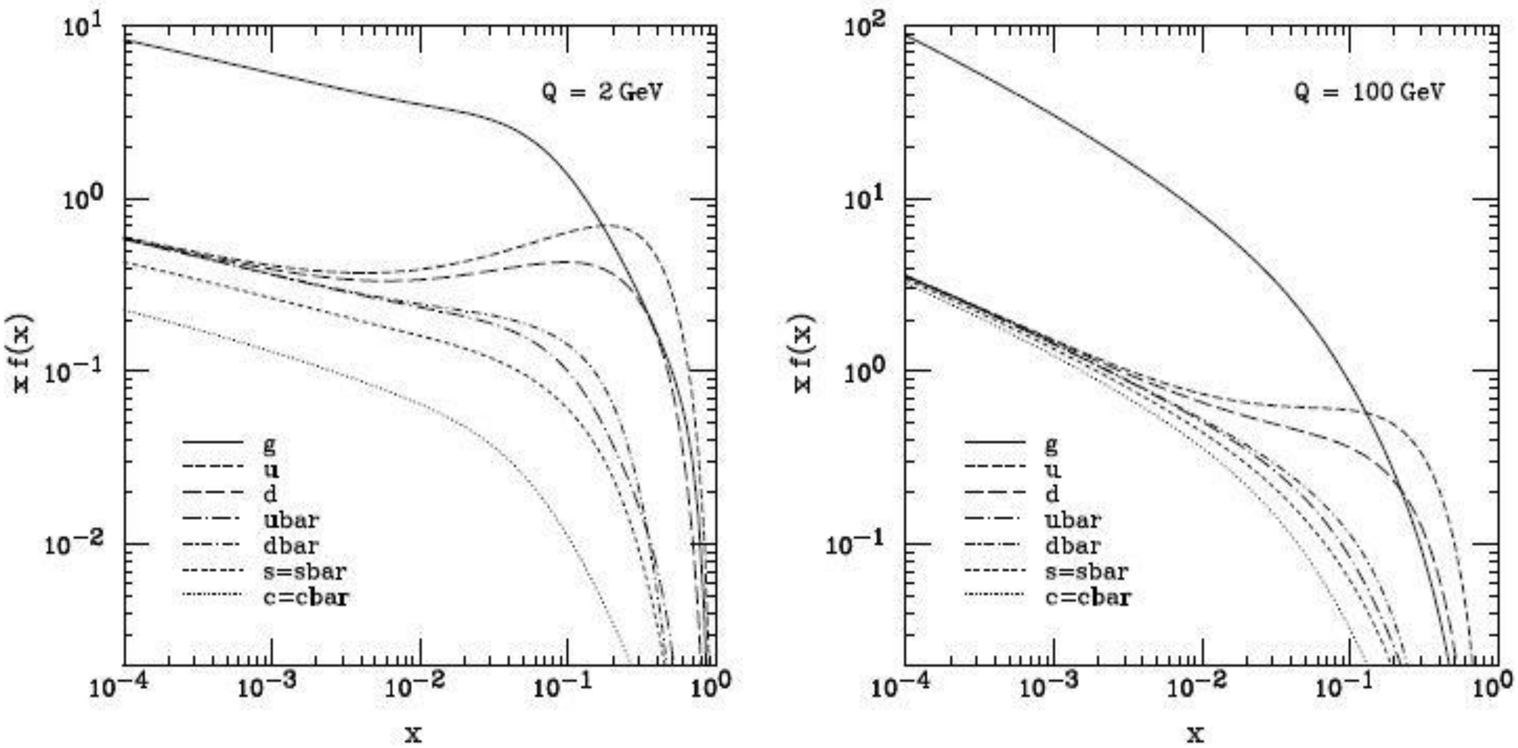
- DIS = deep inelastic lepton nucleon scattering
- Drell-Yan data at hadron colliders
- di-muon data in ν_μ DIS give information on $s(x)$ via $s \to c$ CC transition and $c \to \mu X$ decay
- Inclusive jet production at Tevatron and LHC as input for $g(x)$
-

Example DIS input data with CTEQ6 fit



CTEQ and MRS and NNPDF and ... perform global fits to available data...

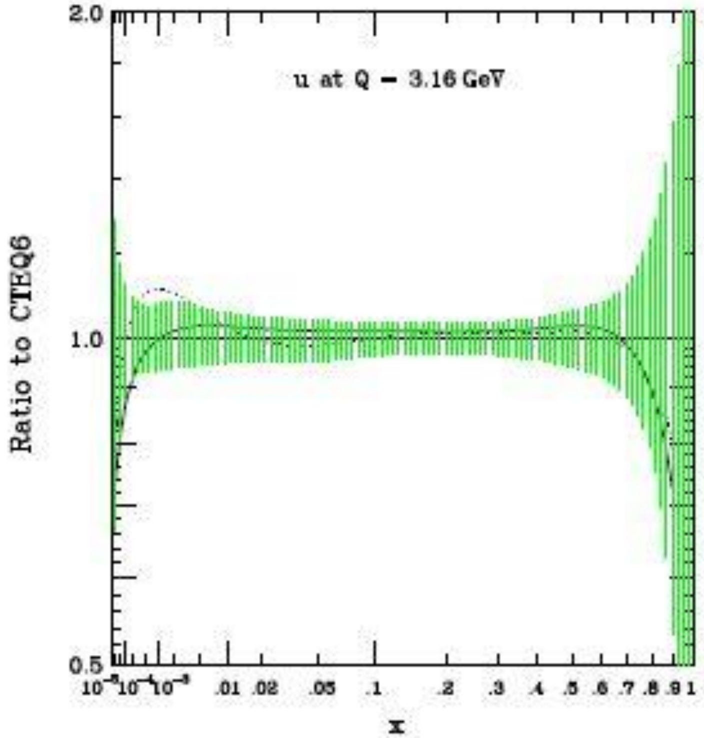
CTEQ6 pdf's at two different scales



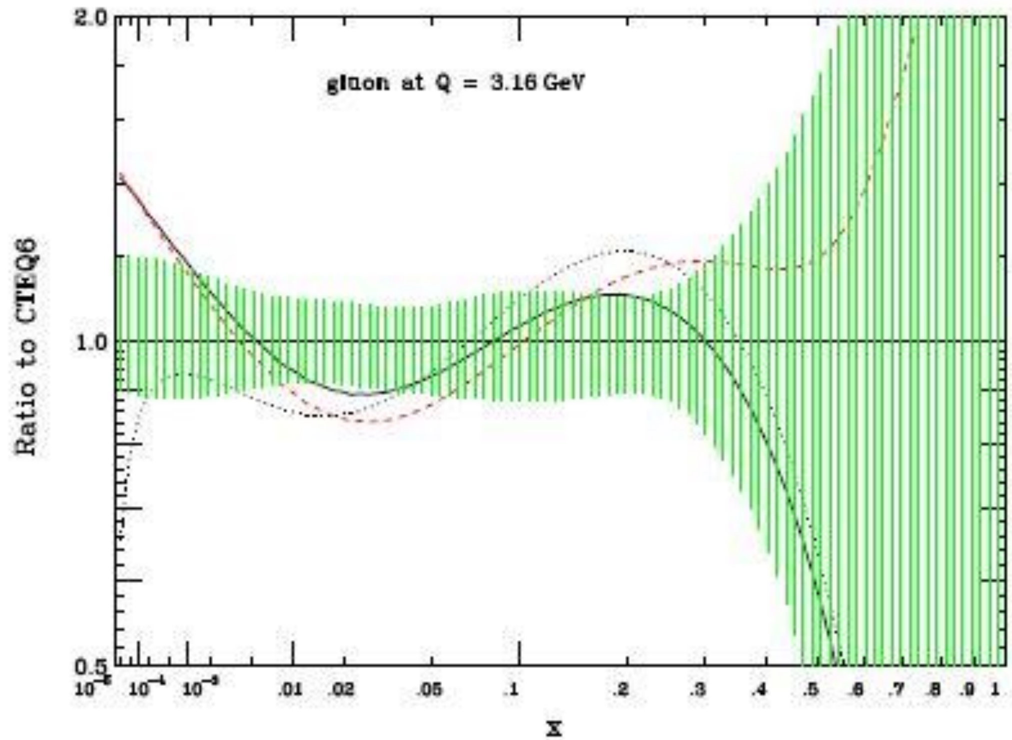
- gluons dominate the $x f_{i/p}(x, Q)$
- large valence u and d quark contributions at $x > 0.01$
- pronounced scale ($Q = \mu_f$) dependence of pdf's

Uncertainties of pdf determinations

relative errors on: $u(x,Q)$ at $Q^2 = 10\,\mathrm{GeV}^2$



$g(x,Q)$ at $Q^2 = 10\,\mathrm{GeV}^2$



Uncertainties of pdfs

Modern pdf parameterizations provide information on uncertainties which arise from

- experimental errors: statistical and systematic
- theory errors, e.g. missing higher orders in cross section calculations

Note: limitations of ansatz for functional form of pdf's cannot be included in error estimates

Typical uncertainties are in the 5–10% range, but much larger at $x \gtrsim 0.3$ for gluons, $x \gtrsim 0.5$ for valence quarks. Note that these ranges are factorization scale dependent!

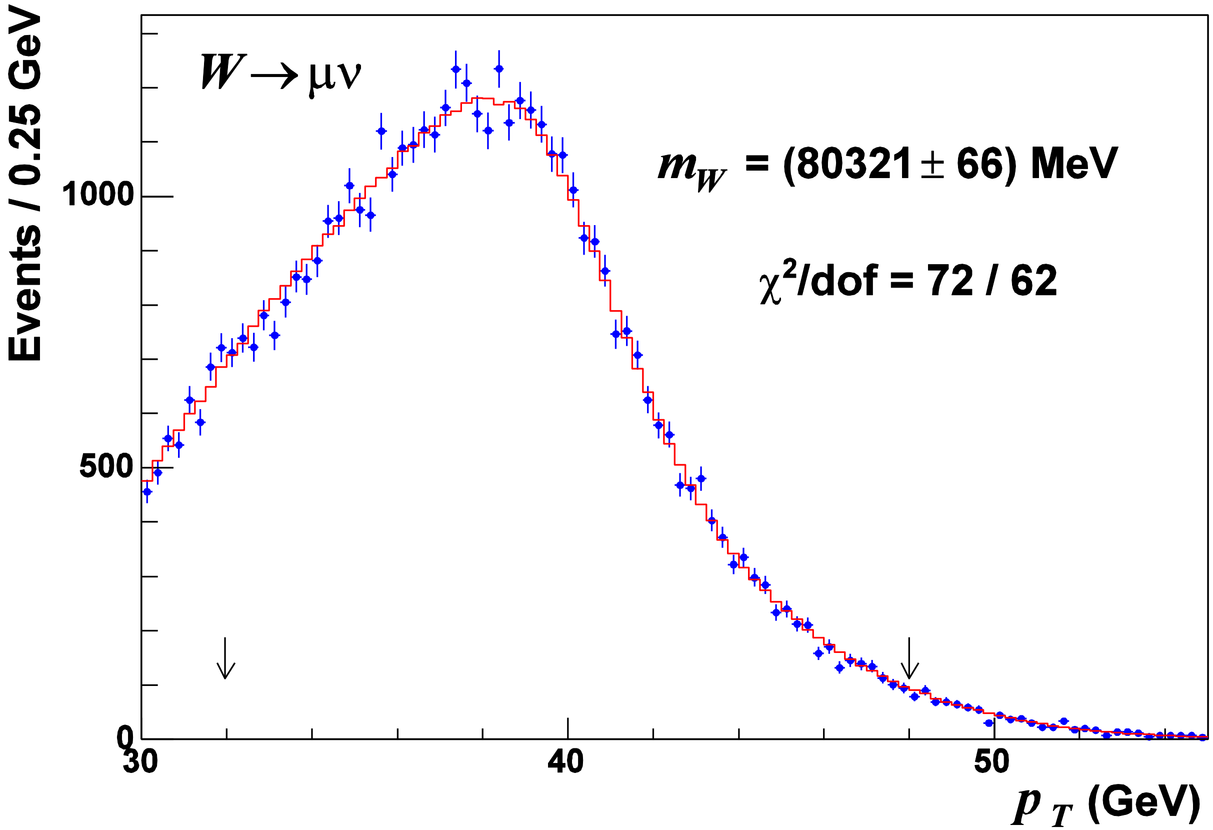
Large selection of pdf's available as C++ packages
(google LHAPDF)

Some errors are correlated and cancel in cross section calculations

Hadron collider kinematics

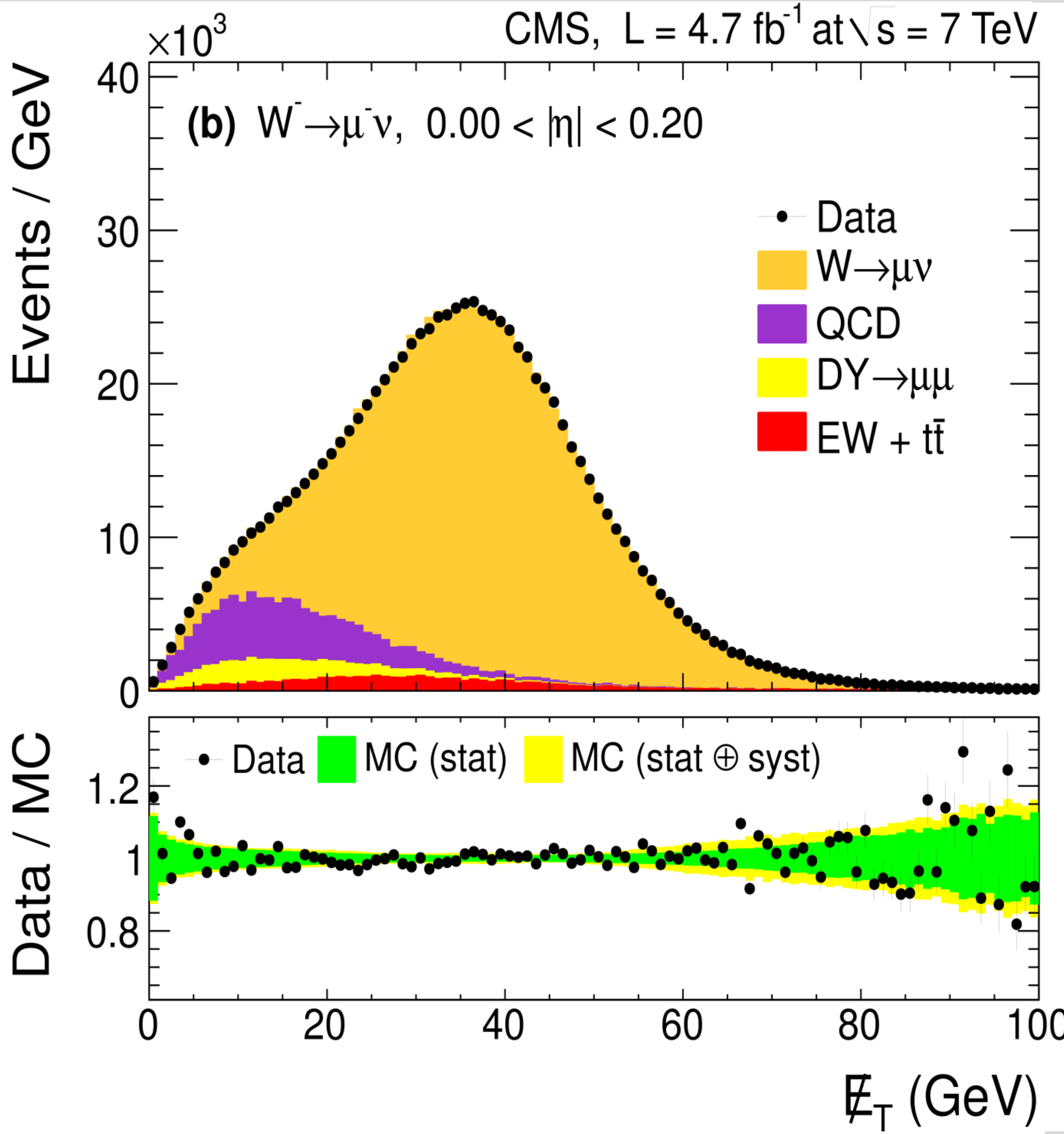
- Rapidity, pseudorapidity and transverse momentum
- W and Z production
- Missing ET and transverse mass
- Transverse momentum distributions

Observed lepton pT distribution at the Tevatron

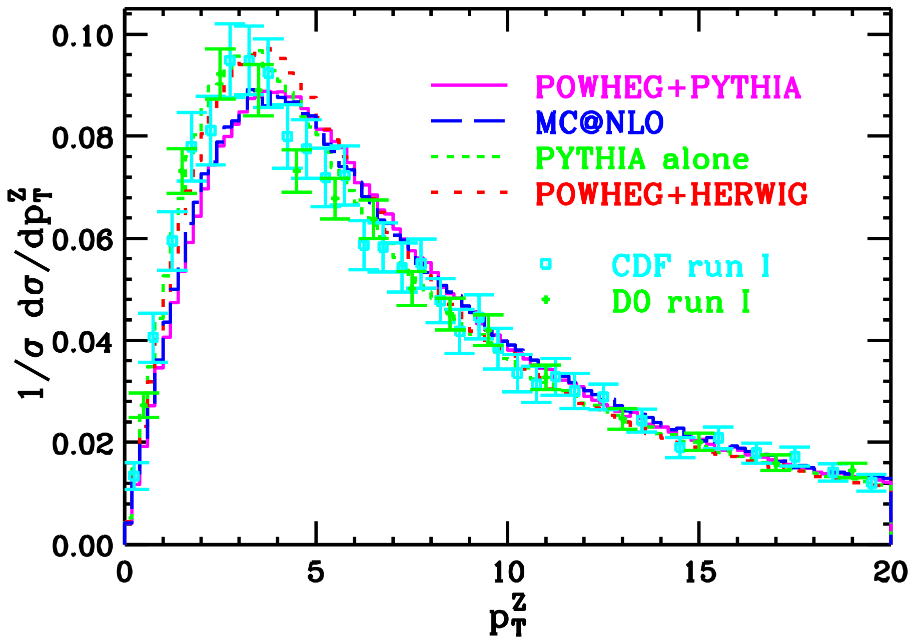


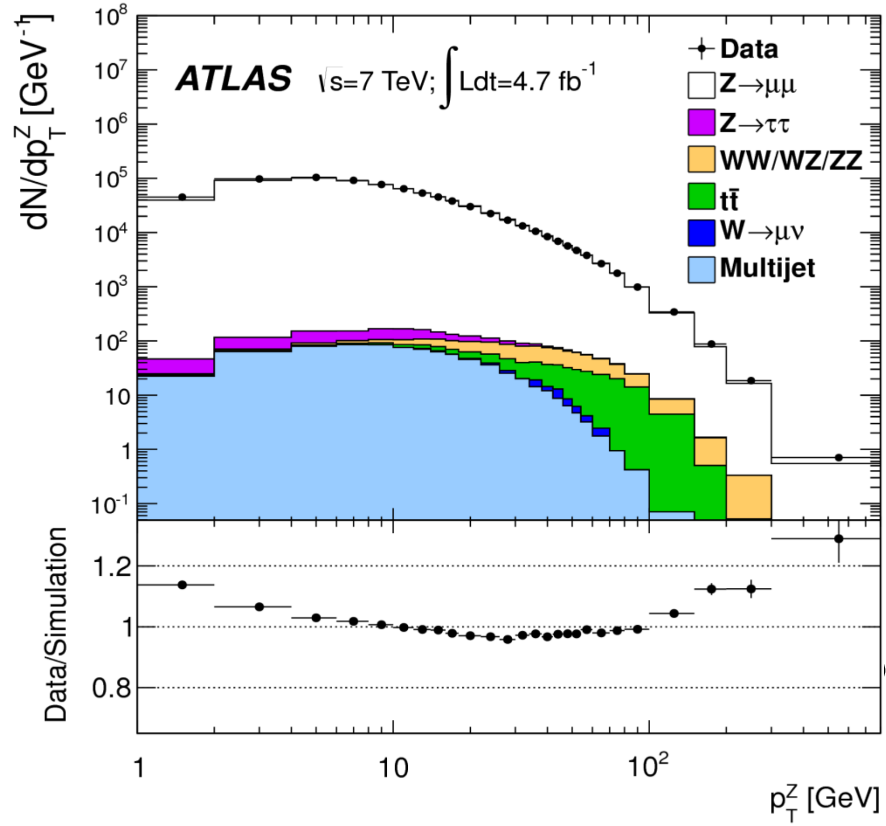
Jacobian peak at mW/2 clearly visible, but smeared out by width effects and due to extra parton emission

Observed neutrino pT distribution at the LHC



Comparison of Z transverse momentum: theory vs. data





Need resummation of gluon emission for correct description of Z transverse momentum distribution

Modern tool: NLO QCD calculation combined with parton shower programs like PYTHIA or Herwig