The Strong Interaction and LHC phenomenology

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Theoretical Physics Graduate School course

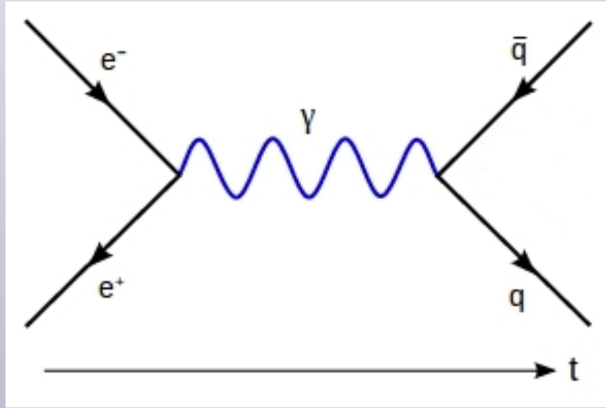
Lecture 6:
Perturbative QCD in hadron-hadron collisions

QCD in electron-positron annihilation

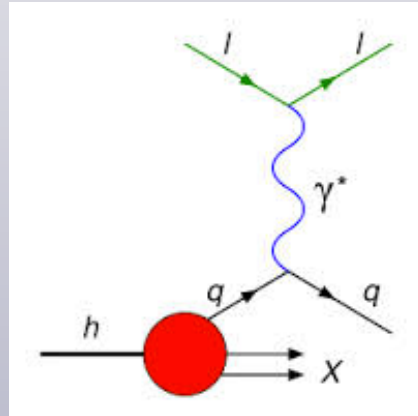
After this introduction to the basic properties of QCD, we now turn to review the application of **perturbative QCD** in **high-energy collisions**

The **QCD processes** that we will study are the following:

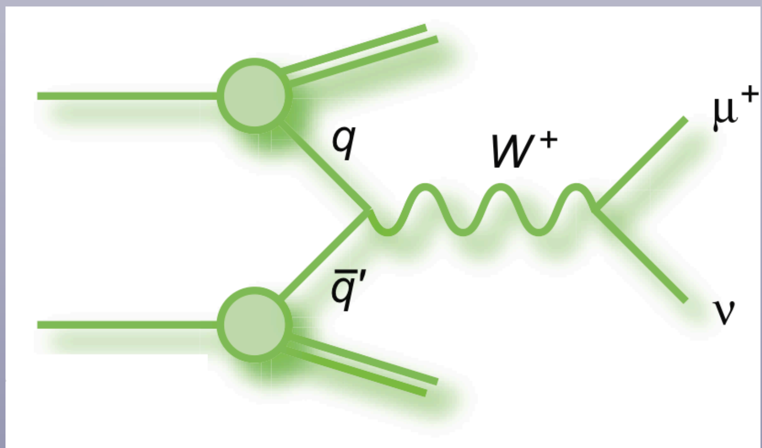
Electron-positron annihilation
No hadrons in initial state



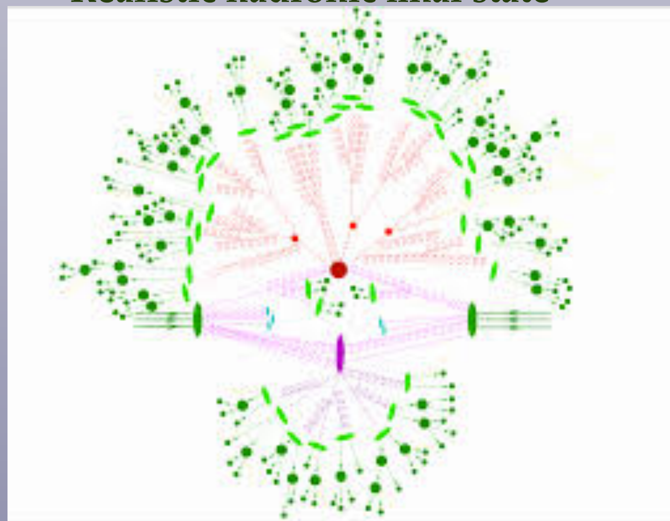
Deep-inelastic scattering
One hadrons in initial state



Hadron collisions
Two hadrons in initial state



Parton showers
Realistic hadronic final state

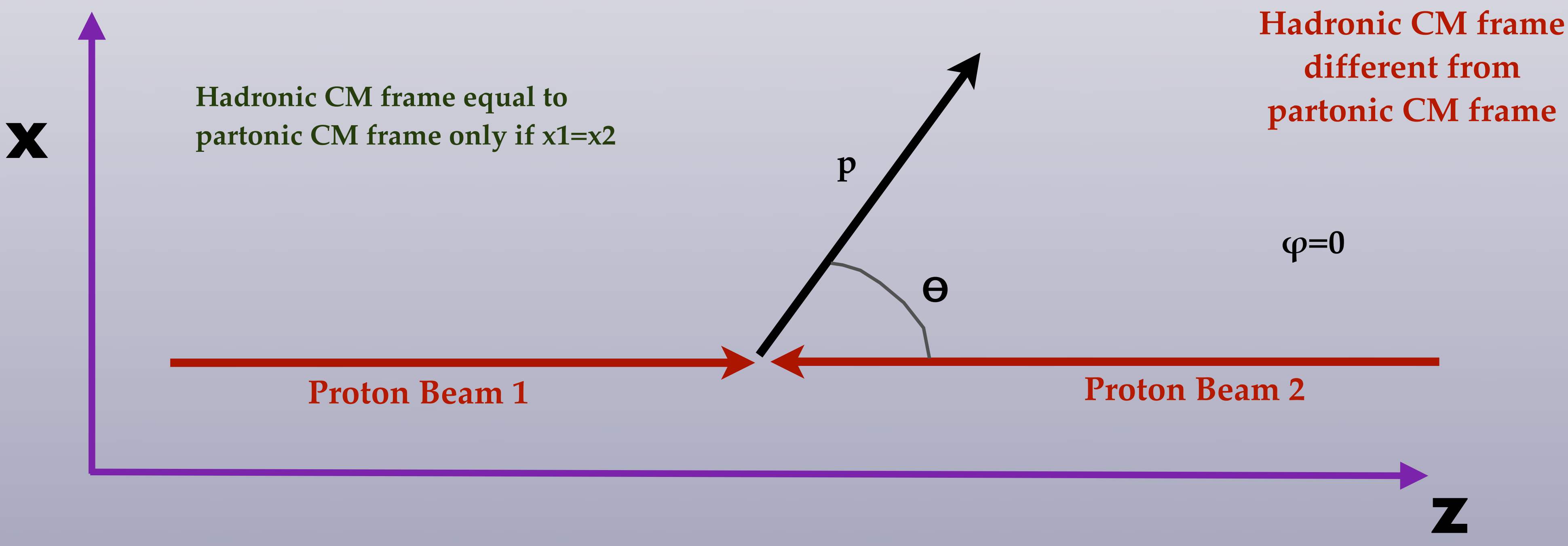


QCD in hadron collisions

After studying **e+e- annihilation** (with no hadrons in the initial state) and **deep-inelastic scattering** (one hadron in the initial state), now perturbative QCD in **hadron collisions**, like the Large Hadron Collider

In hadron collisions, the most suitable event description is provided by using quantities that are either **invariant or that transform simply under longitudinal boosts**, since in general the initial **parton-parton state has a non-zero longitudinal momentum** (whose distribution is determined by the PDFs)

A suitable parametrization of the four-momentum of a particle in hadron collisions is



$$p = (E, p_x, p_y, p_z) = \left(\sqrt{\vec{p}^2 + m^2}, |\vec{p}| \sin\theta \cos\phi, |\vec{p}| \sin\theta \sin\phi, |\vec{p}| \cos\theta \right)$$

In proton-proton collisions, the **total longitudinal momentum of the colliding system** (that is, in the beam direction) is in general **unknown**

QCD in hadron collisions

$$p = (E, p_x, p_y, p_z) = \left(\sqrt{\vec{p}^2 + m^2}, |\vec{p}|\sin\theta\,\cos\phi, |\vec{p}|\sin\theta\,\sin\phi, |\vec{p}|\cos\theta\right)$$

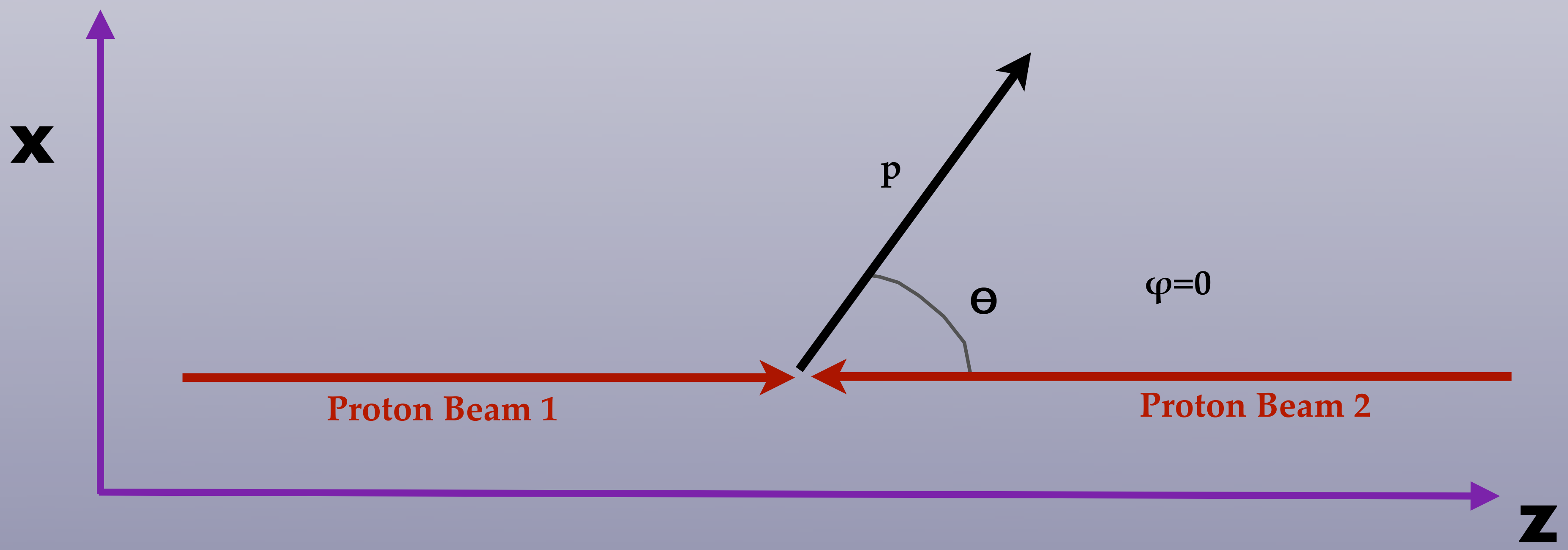
It is useful to express the four-momentum in terms of the particle **rapidity** and **transverse mass**

$$y \equiv \frac{1}{2}\ln\frac{E+p_z}{E-p_z} \qquad m_T = \sqrt{p_T^2 + m^2}$$

Exercise: check that the two parametrizations of **p** are equivalent

$$p = (E, p_x, p_y, p_z) = (m_T \cosh y, |p_T|\cos\phi, |p_T|\sin\phi, m_T \sinh y)$$

The rapidity transforms additively under a **longitudinal boost:** easy transformation from partonic center of mass system to hadronic center of mass system + the difference of rapidities of two particles is **boost-invariant**



QCD in hadron collisions

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The rapidity transforms additively under a **longitudinal boost:** easy transformation from **partonic center of mass system** to **hadronic center of mass system**

To verify this, note that under a **longitudinal boost** the four-momentum transforms as

$$p' = \gamma(E - \beta\, p_z, p_x, p_y, -\beta\, E + p_z)$$

Recall the usual boost parameters

$$\beta = v \qquad \gamma = \frac{1}{\sqrt{1 - v^2}}$$

and that is is easy to see that in this case the **rapidity transforms additively**

$$y' = y + \frac{1}{2}\log\frac{1-\beta}{1+\beta}$$

So the **difference between rapidities** of two particles is **boost-invariant,** and thus potentially useful observable

$$\Delta y' \equiv y_1' - y_2' = \Delta y \equiv y_1 - y_2$$

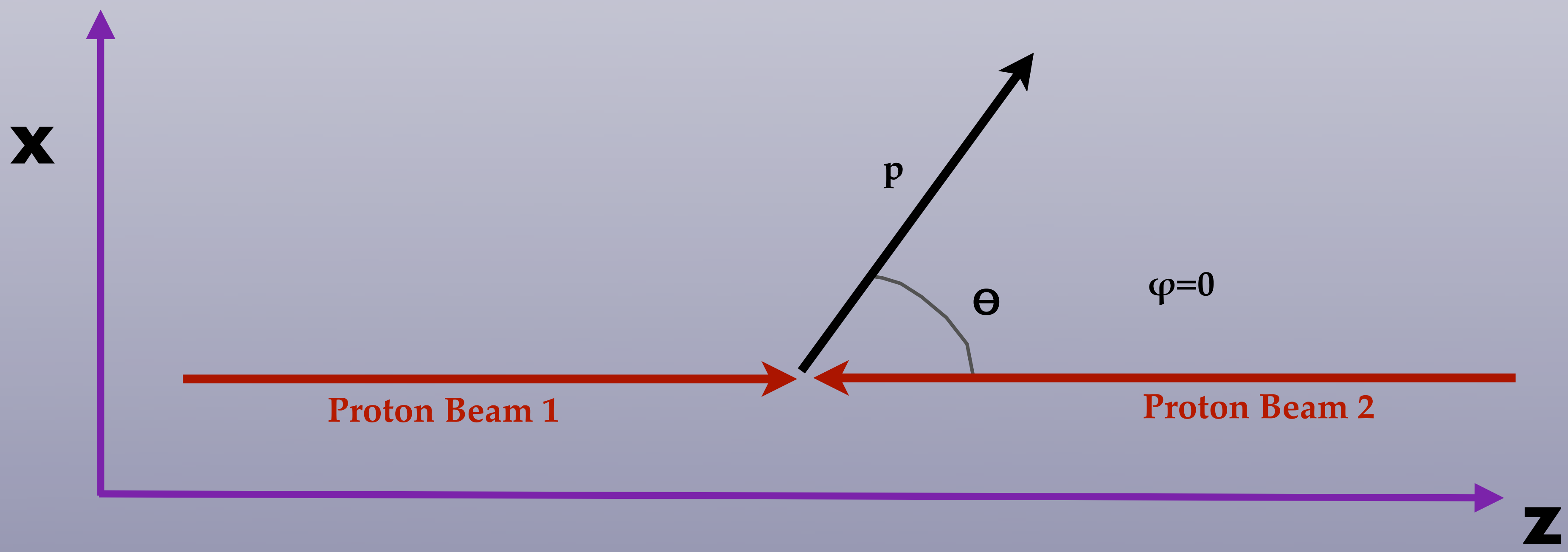
QCD in hadron collisions

$$y \equiv \frac{1}{2} \ln \frac{E + p_z}{E - p_z} \qquad m_T = \sqrt{p_T^2 + m^2}$$

For particles of **negligible mass** compared to other scales of the process the above expressions simplify to

$$y \simeq -\log \tan \frac{\theta}{2} \equiv \eta \qquad m_T \simeq p_T$$

where we have defined the **pseudorapidity,** which can be translated directly to the **detector geometric acceptance**, and is widely used in experimental measurements



Rapidity coverage of LHC detectors

Achieving the **maximum possible coverage in rapidity** is important for many important LHC processes

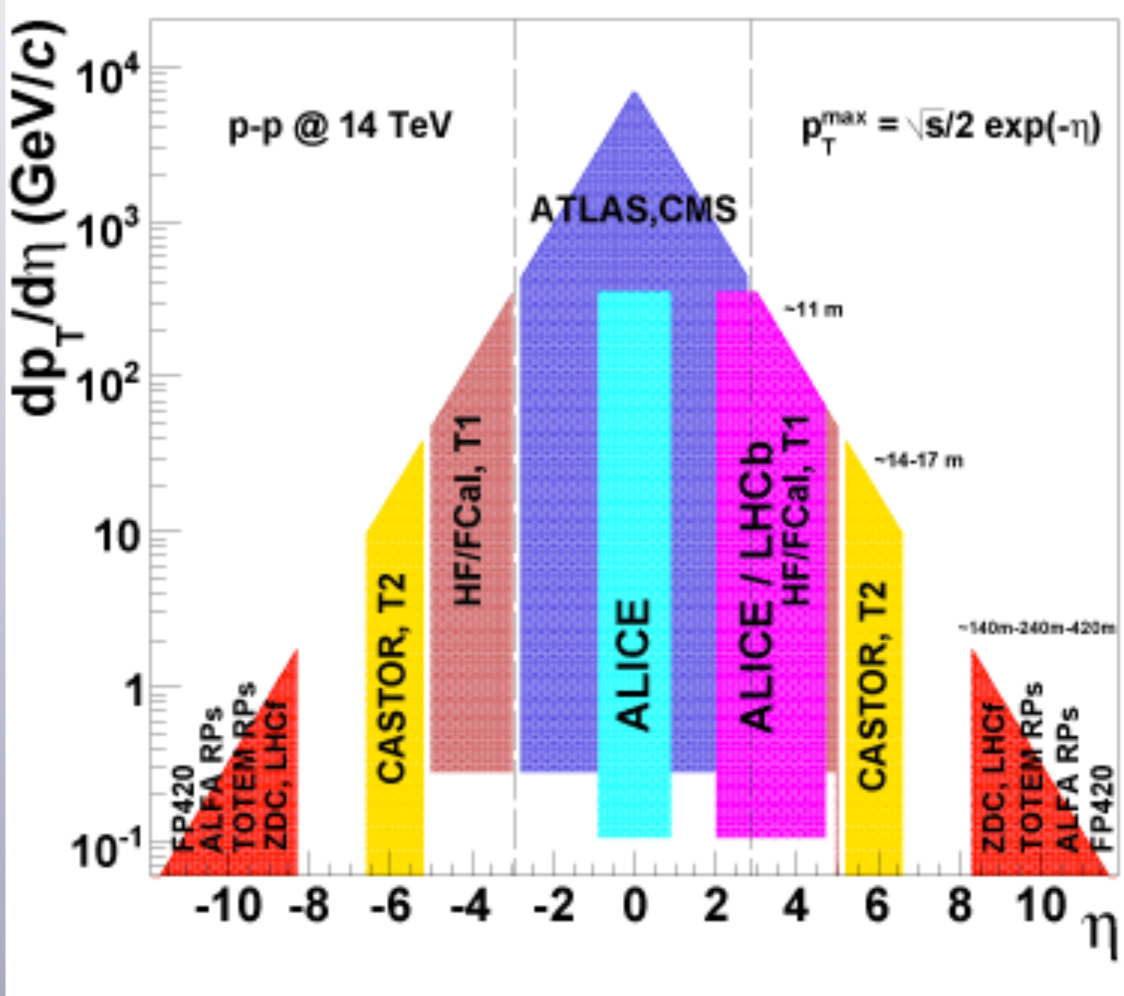


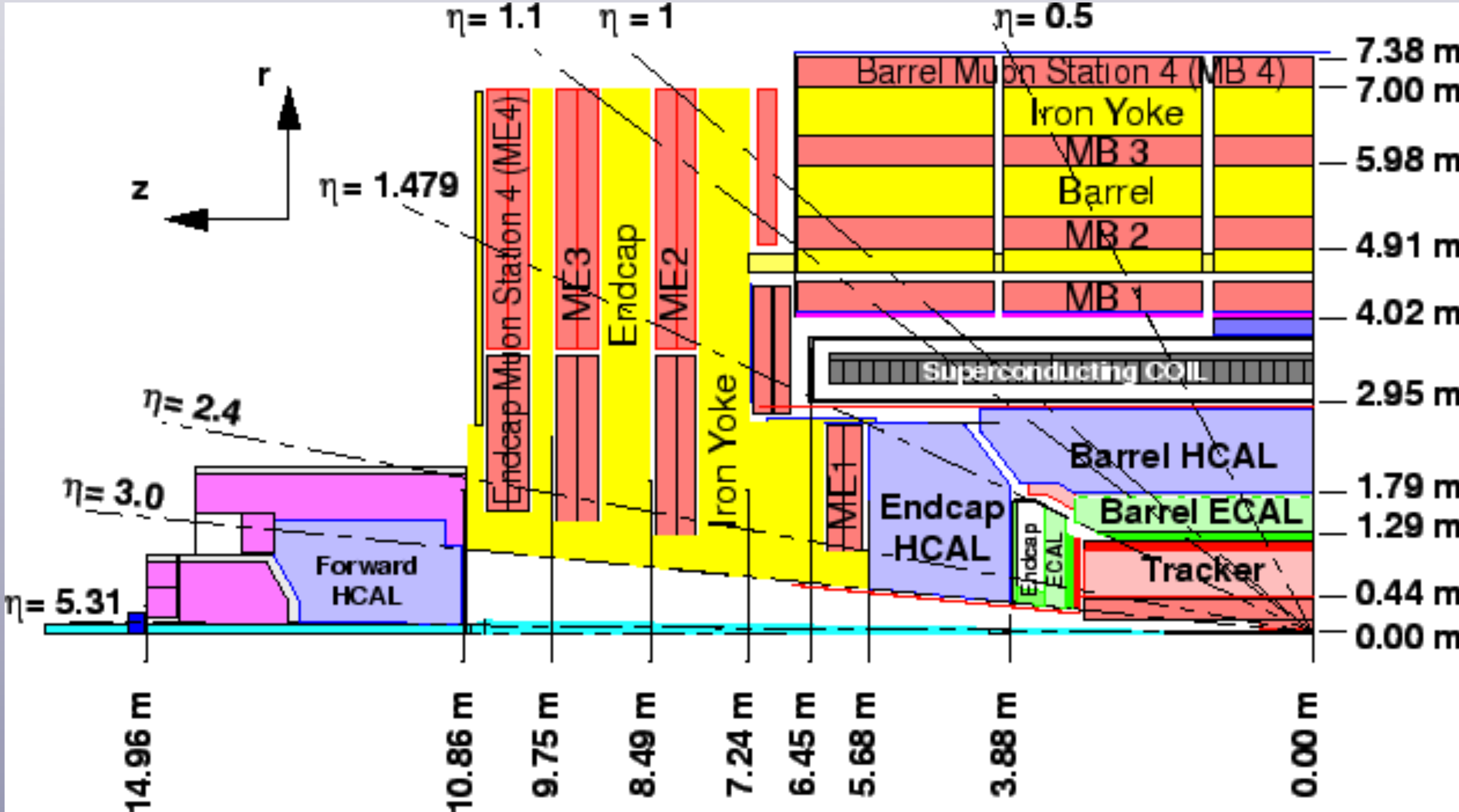
FIG. 3: Approximate p_T-η coverage of current (and proposed) detectors at the LHC (adapted from [2]).

Rapidity coverage of LHC detectors

Achieving the **maximum possible coverage in rapidity** is important for many important LHC processes

For **ATLAS** and **CMS, electrons and muons** can be detected only in the central region (barrel and endcap electromagnetic calorimeters)

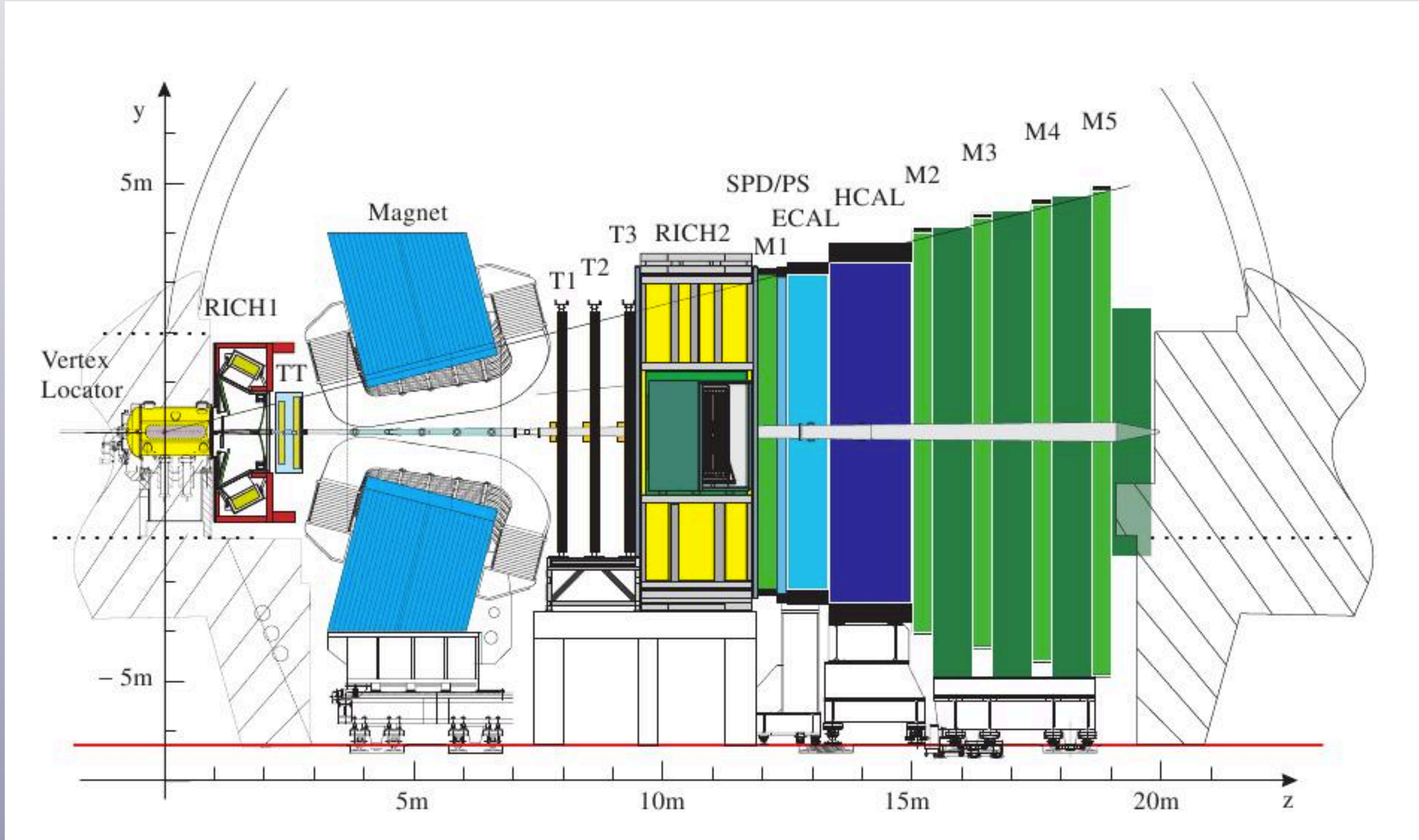
For jets and hadrons, hadronic calorimetry extends up to pseudo-rapidities of up to 4.5 or 5.0. Essential for many processes, like Higgs production in **vector-boson fusion**



Rapidity coverage of LHC detectors

Achieving the **maximum possible coverage in rapidity** is important for many important LHC processes

The **LHCb detector** covers the most forward region in pseudo-rapidity: access to **unique kinematical region**



QCD in hadron collisions

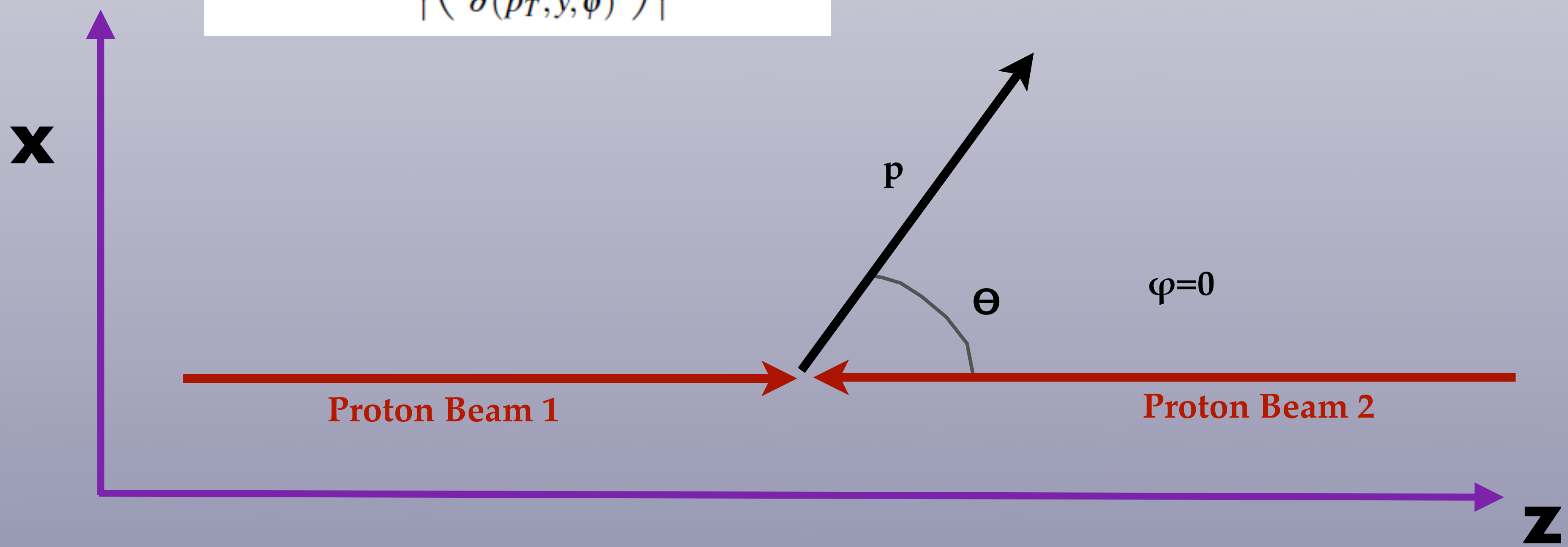
$$p = (E, p_x, p_y, p_z) = (m_T \cosh y, |p_T| \cos\phi, |p_T| \sin\phi, m_T \sinh y)$$

Another useful formula in hadronic collisions is that the **single particle phase space is uniform in transverse momentum and rapidity**

$$\frac{d^3 p}{2E(2\pi)^2} = \frac{1}{2(2\pi)^3} d^2 p_T \, dy$$

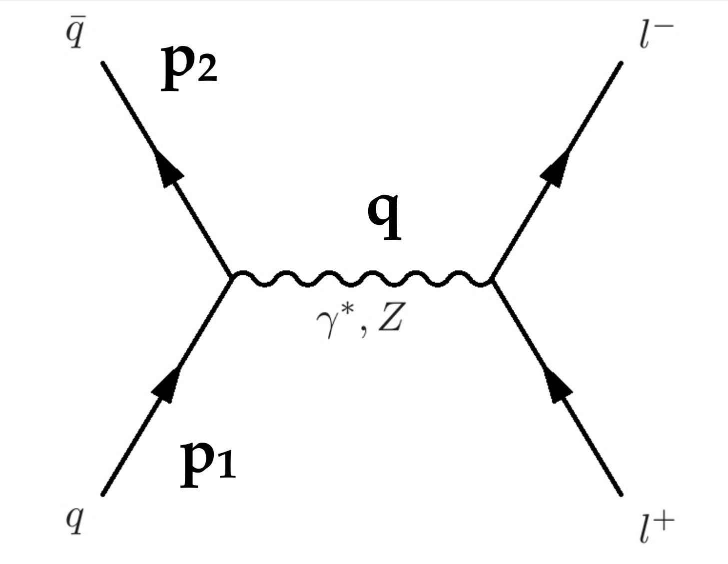
Exercise: derive this expression, including the Jacobian of the change of variables

$$dp_x dp_y dp_z = \left| \left(\frac{\partial(p_x, p_y, p_z)}{\partial(p_T, y, \phi)} \right) \right| dp_T \, dy \, d\phi$$



Drell-Yan production in hadron collisions

One of the simplest process that can be studied in hadronic collisions is the so-called **Drell-Yan** process, the production of a **single electroweak gauge boson**, a W or a Z (characteristic of **2 -> 1 kinematics**)



The kinematics of this process are very simple

If we are in the **hadronic center of mass frame,** and each quark carries a **fraction x_1 and x_2 of proton momentum**

$$
\begin{aligned}
p_1 &= (x_1 E_{\text{beam}}/2, 0, 0, x_1 E_{\text{beam}}/2) \\
p_2 &= (x_2 E_{\text{beam}}/2, 0, 0, -x_2 E_{\text{beam}}/2) \\
q &= ((x_1+x_2) E_{\text{beam}}/2, 0, 0, (x_1-x_2) E_{\text{beam}}/2)
\end{aligned}
$$

Let's consider for simplicity on-shell **W+ production**

In this process, **kinematics are fixed** once gauge boson rapidity is specified

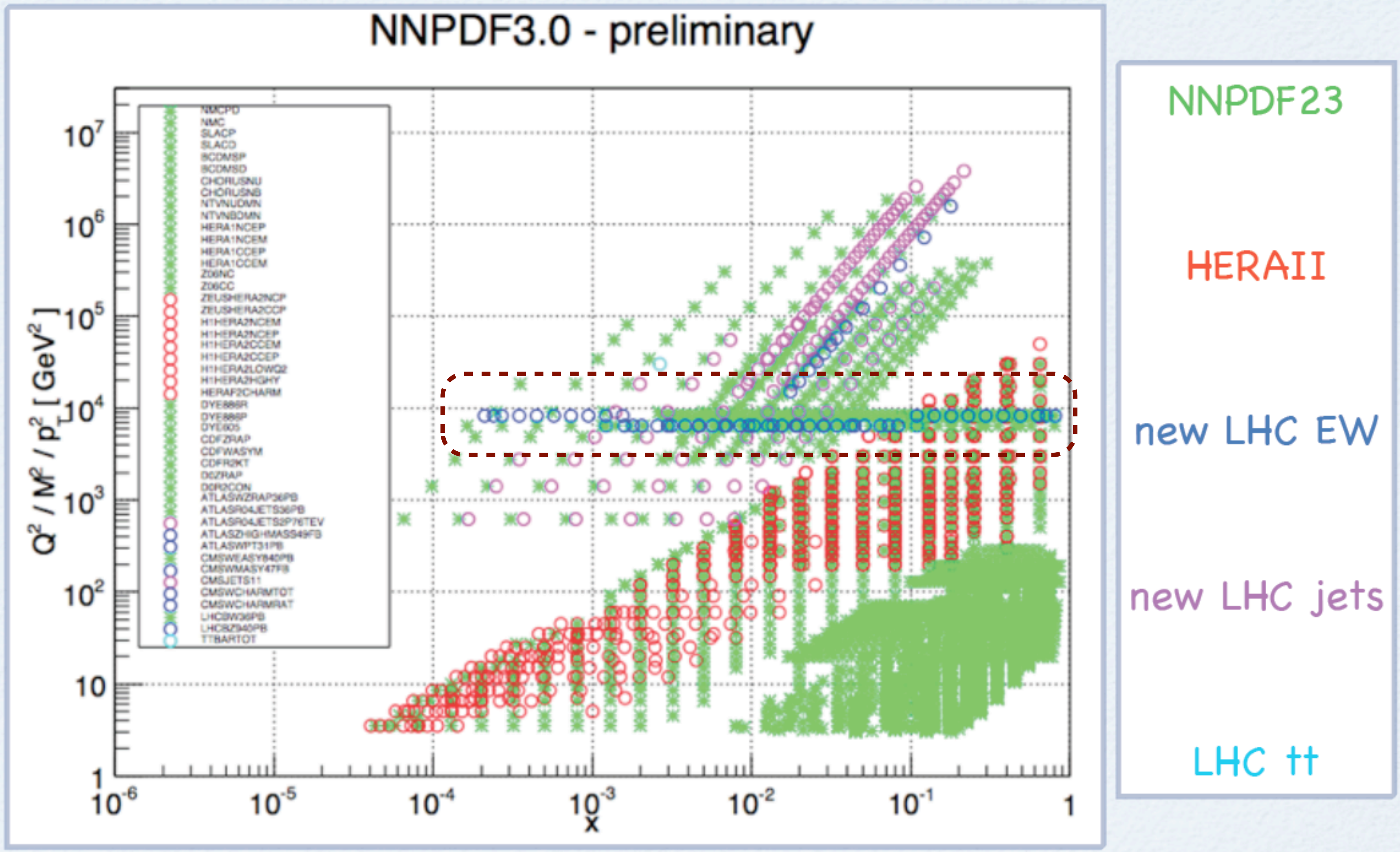
$$
y = \frac{1}{2}\log\frac{q_0+q_z}{q_0-q_z} = \frac{1}{2}\log\frac{x_1}{x_2} \qquad x_1 x_2 s = M_W^2
$$

So that the values of the **Bjorken-x** of the quark PDFs that are relevant in this process are

$$
x_1 = \frac{M_W}{\sqrt{s}} e^{y} \qquad x_2 = \frac{M_W}{\sqrt{s}} e^{-y}
$$

Drell-Yan production in hadron collisions

LHC DY data now cover a wide range of **Bjorken-x from 10^{-4} to 1** between ATLAS, CMS and LHCb



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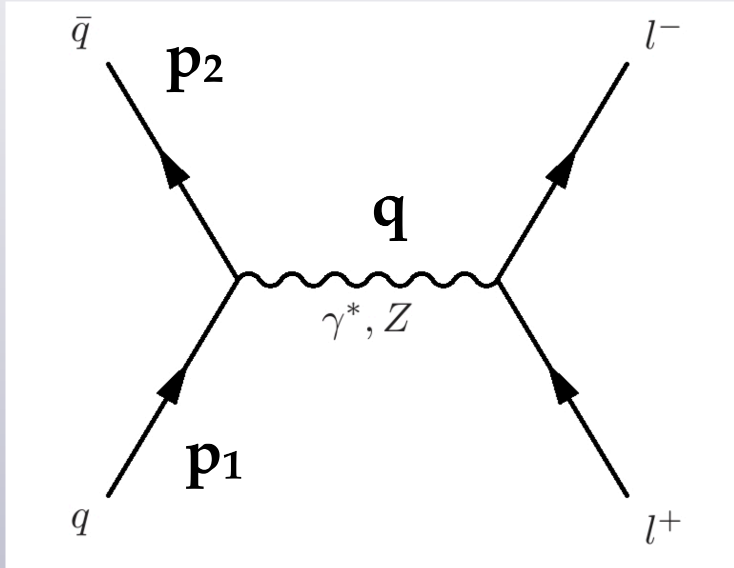

Using the QED Feynman rules, the amplitude for the hadroproduction of a gauge boson reads

$$\mathcal{M} = g\,\hat{v}(p_2)\,\gamma^\mu\,u(p_1)$$

and the partonic cross-section will be

$$\hat{\sigma} = \frac{1}{2\hat{s}}\frac{1}{4}\frac{1}{9}\int d\phi_1 \sum_{\text{spin,col}} |\mathcal{M}|^2$$

Flux factor

Spin average

Color average

Doing this simple calculation **(exercise)** we find that the partonic cross-section is

$$\hat{\sigma} = \frac{4\pi^2}{3}\frac{g^2}{4\pi}\delta(\hat{s} - M_V^2)$$

Tip: the one-particle phase space can be written as

$$d\phi_1 = \int \frac{d^3q}{2q^0(2\pi)^3}(2\pi)^4\delta^{(4)}(p_1 + p_2 - q) = 2\pi\,\delta((p_1+p_2)^2 - M_V^2)$$

Drell-Yan production in hadron collisions

To transform the partonic cross-section into the hadronic cross-section, in the parton model we need to include the **Parton Distribution Functions** for the various **relevant quark combinations**

$$\hat{\sigma} = \frac{4\pi^2}{3}\frac{g^2}{4\pi}\delta(\hat{s} - M_V^2)$$

For instance, in the case of **W+ production,** assuming a diagonal CKM matrix and that only first generation of quarks contribute, we find

$$\begin{aligned}\sigma_{W^+} &= \int dx_1\, dx_2\, [f_u(x_1)f_{\bar{d}}(x_2) + f_{\bar{d}}(x_1)f_u(x_2)] \times \frac{\pi^2}{3}\frac{\alpha_{\rm QED}}{\sin^2\theta_W}\delta(sx_1x_2 - M_W^2) \\ &= \frac{\pi^2}{3}\frac{\alpha_{\rm QED}}{\sin^2\theta_W}\frac{1}{s}\int_0^1 \frac{dx_1}{x_1}\left[f_u(x_1)f_{\bar{d}}\left(\frac{M_W^2}{x_1 s}\right) + f_{\bar{d}}(x_1)f_u\left(\frac{M_W^2}{x_1 s}\right)\right]\end{aligned}$$

It is interesting to measure the cross-section **differential in the vector boson rapidity**, since then we find a transparent relation on the proton PDFs. In this case we find the simple expression

$$\frac{d\sigma_{W^+}}{dy_{W^+}} = \frac{\pi^2}{3}\frac{\alpha_{\rm QED}}{\sin^2\theta_W s}[f_u(x_1)f_{\bar{d}}(x_2) + f_{\bar{d}}(x_1)f_u(x_2)]$$

$$x_1 = \frac{M_W}{\sqrt{s}}e^y \qquad x_2 = \frac{M_W}{\sqrt{s}}e^{-y}$$

Therefore, such distribution provides a **direct measurement of the quark PDFs**

Drell-Yan production in hadron collisions

For each process, the contribution of different quark flavor combinations will be different

The Drell-Yan process offers a direct handle on the **quark flavor separation in the proton**

W+	u*dbar u*sbar c*dbar
W-	d*ubar s*ubar d*cbar
Z	u*ubar d*dbar s*sbar

Drell-Yan production in hadron collisions

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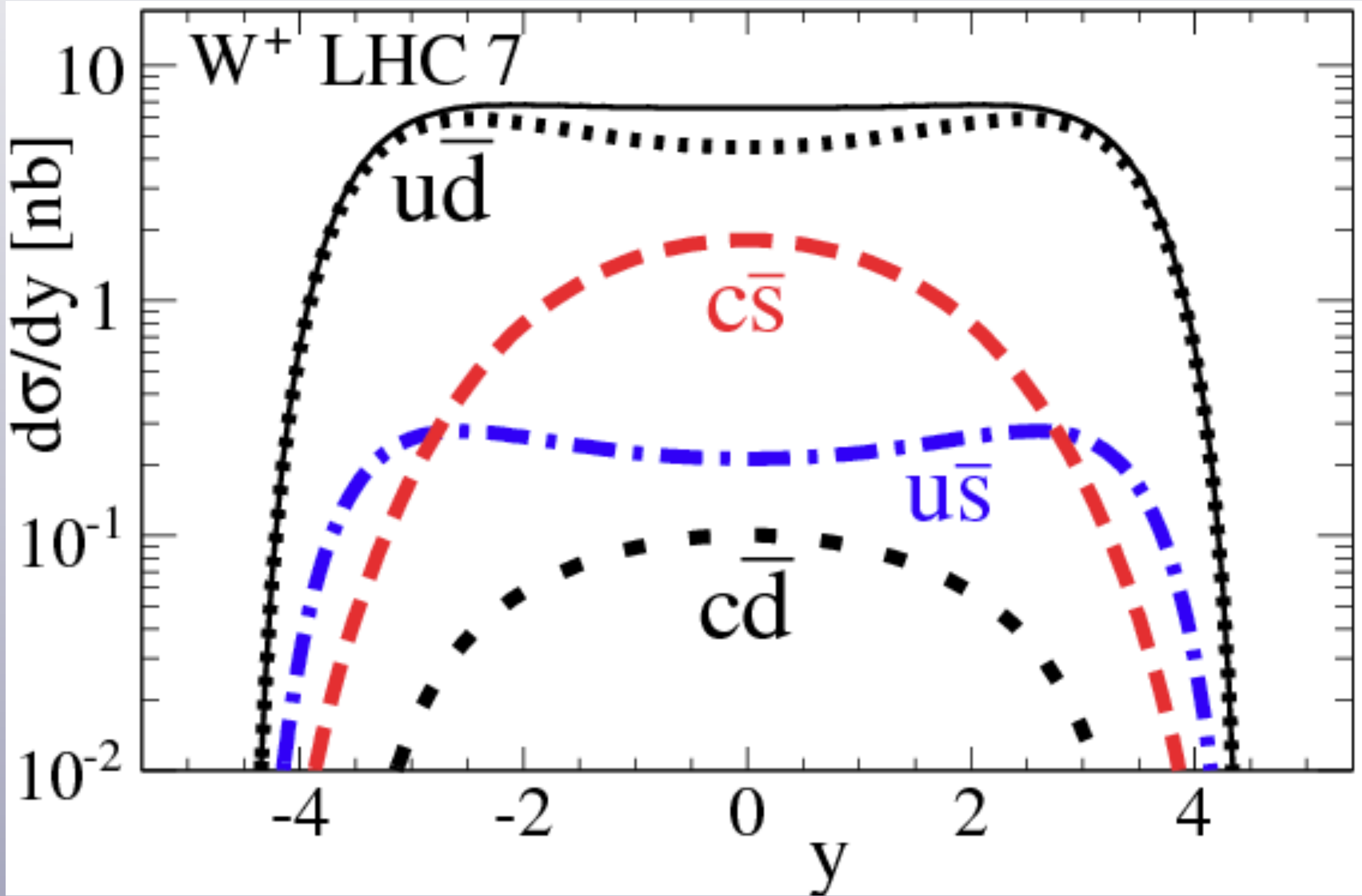


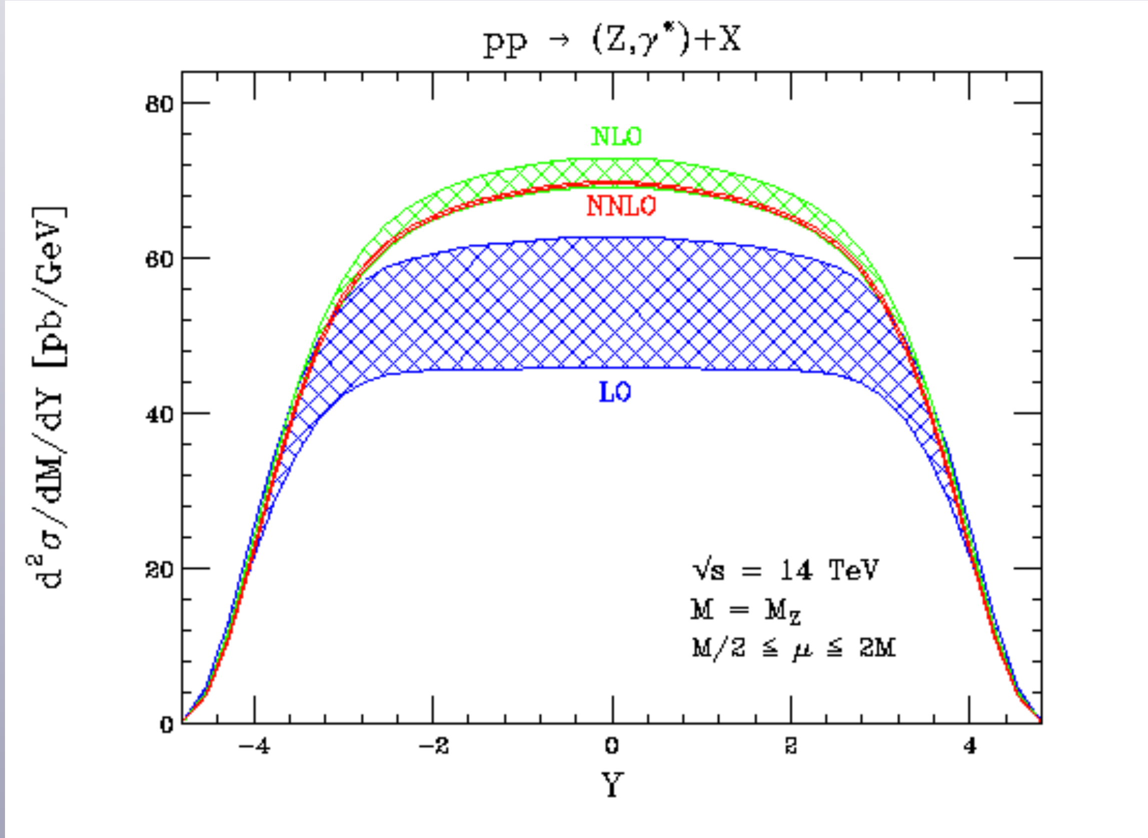
Accurately modeling the contribution from **second-generation quarks** is essential for precision physics

Drell-Yan production in hadron collisions

$$\frac{d\sigma_{W^+}}{dy_{W^+}} = \frac{\pi^2}{3}\frac{\alpha_{\rm QED}}{\sin^2\theta_W\, s}\left[f_u(x_1)f_{\bar d}(x_2) + f_{\bar d}(x_1)f_u(x_2)\right]$$

$$x_1 = \frac{M_W}{\sqrt{s}}e^{y} \qquad x_2 = \frac{M_W}{\sqrt{s}}e^{-y}$$

In perturbative QCD, the full **NNLO result** is available for this distribution



Note the dramatic decrease in **theoretical (scale) uncertainties** from LO to NNLO

Higher order QCD calculations are an essential tool for LHC phenomenology

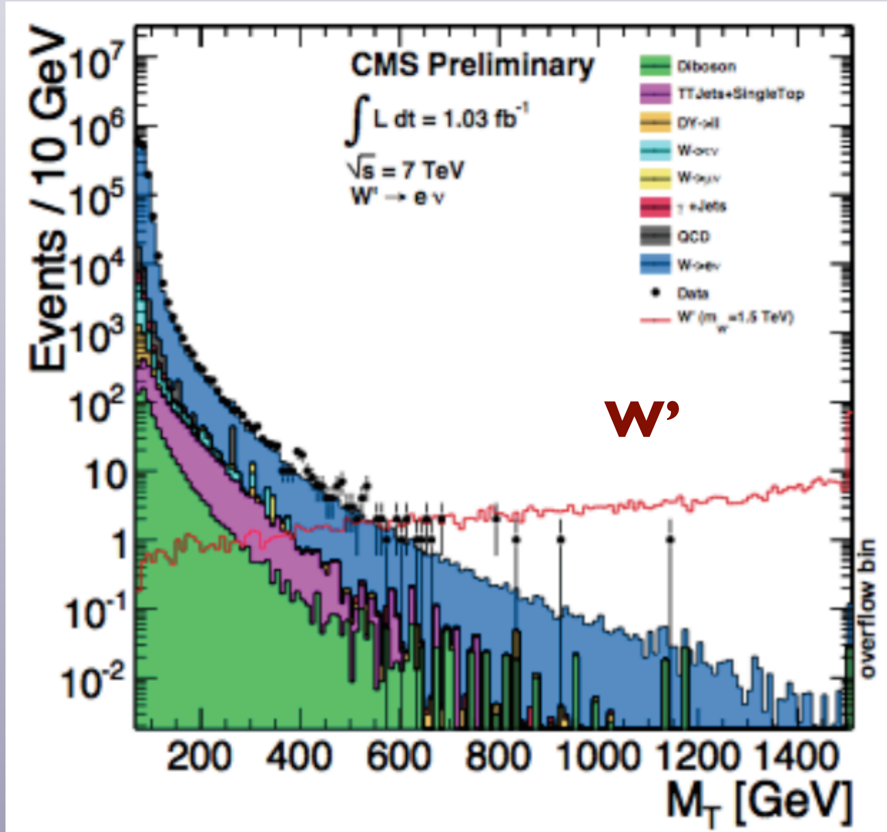
Essential input for **global PDF analysis,** as we will discuss later in the course

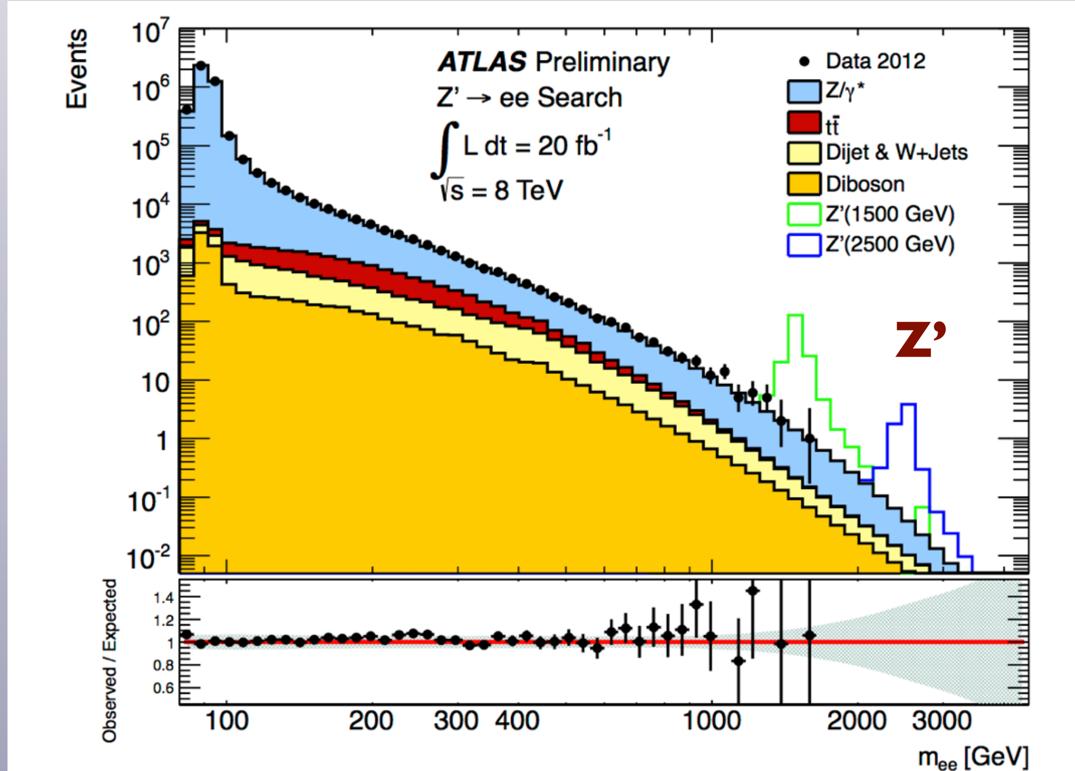
Drell-Yan production in hadron collisions

$$\frac{d\sigma_{W^+}}{dy_{W^+}} = \frac{\pi^2}{3}\frac{\alpha_{\rm QED}}{\sin^2\theta_W\, s}\left[f_u(x_1)f_{\bar{d}}(x_2) + f_{\bar{d}}(x_1)f_u(x_2)\right]$$

$$x_1 = \frac{M_W}{\sqrt{s}}e^{y} \qquad x_2 = \frac{M_W}{\sqrt{s}}e^{-y}$$

Drell-Yan production is also essential for searches, for instance of extra gauge bosons **W'** and





Improving QCD predictions translate into more **stringent searches for new physics**

Jet production in hadron collisions

Another important process in hadron collisions is **jet production**

In hadroproduction, this is the simplest process that exhibits **2 -> 2 kinematics**

In the **parton model**, we need to convolute all partonic cross-sections for **quark and gluon scattering** with the appropriate **parton distributions**

$$d\sigma^{\rm jet} = \sum_{ijkl} dx_1\, dx_2\, f_i(x_1)\, f_j(x_2)\, \frac{d\hat{\sigma}_{ij\to kl}}{d\Phi_2}\, d\Phi_2$$

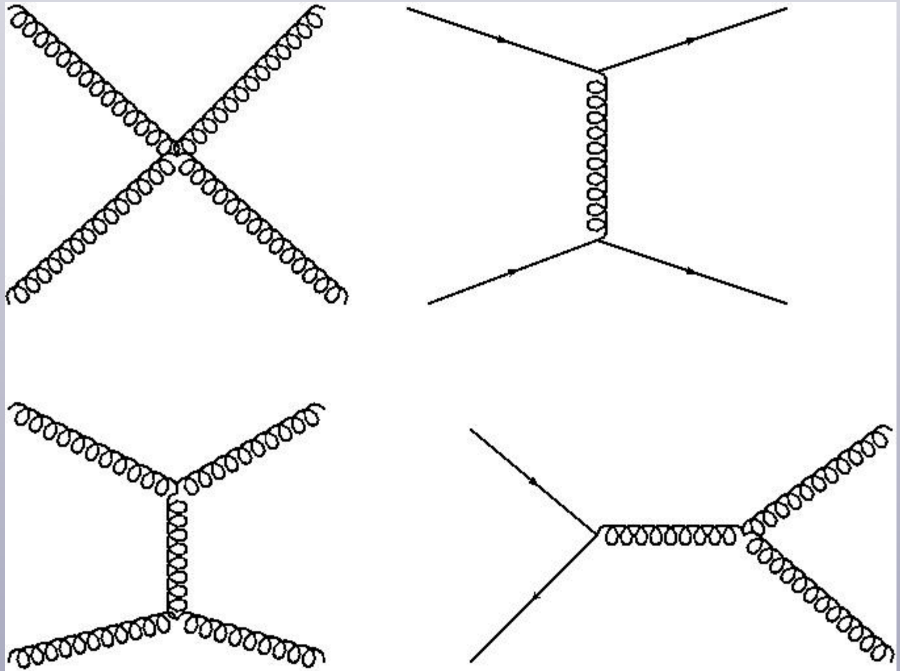
Hadronic cross-section

PDFs for initial state partons

Partonic cross-section

two-particle phase space

Some of the processes that contribute to hadronic jet production at leading order



Simplest genuine QCD process in pp collisions

The various **partonic cross-sections in the different channels** can be computed using the QCD Feynman rules

Process	$\frac{d\hat{\sigma}}{d\Phi_2}$
$qq' \to qq'$	$\frac{1}{2\hat{s}}\frac{4}{9}\frac{\hat{s}^2+\hat{u}^2}{\hat{t}^2}$
$qq \to qq$	$\frac{1}{2}\frac{1}{2\hat{s}}\left[\frac{4}{9}\left(\frac{\hat{s}^2+\hat{u}^2}{\hat{t}^2}+\frac{\hat{s}^2+\hat{t}^2}{\hat{u}^2}\right)-\frac{8}{27}\frac{\hat{s}^2}{\hat{u}\hat{t}}\right]$
$q\bar{q} \to q'\bar{q}'$	$\frac{1}{2\hat{s}}\frac{4}{9}\frac{\hat{t}^2+\hat{u}^2}{\hat{s}^2}$
$q\bar{q} \to q\bar{q}$	$\frac{1}{2\hat{s}}\left[\frac{4}{9}\left(\frac{\hat{s}^2+\hat{u}^2}{\hat{t}^2}+\frac{\hat{t}^2+\hat{u}^2}{\hat{s}^2}\right)-\frac{8}{27}\frac{\hat{u}^2}{\hat{s}\hat{t}}\right]$
$q\bar{q} \to gg$	$\frac{1}{2}\frac{1}{2\hat{s}}\left[\frac{32}{27}\frac{\hat{t}^2+\hat{u}^2}{\hat{t}\hat{u}}-\frac{8}{3}\frac{\hat{t}^2+\hat{u}^2}{\hat{s}^2}\right]$
$gg \to q\bar{q}$	$\frac{1}{2\hat{s}}\left[\frac{1}{6}\frac{\hat{t}^2+\hat{u}^2}{\hat{t}\hat{u}}-\frac{3}{8}\frac{\hat{t}^2+\hat{u}^2}{\hat{s}^2}\right]$
$gq \to gq$	$\frac{1}{2\hat{s}}\left[-\frac{4}{9}\frac{\hat{s}^2+\hat{u}^2}{\hat{s}\hat{u}}+\frac{\hat{u}^2+\hat{s}^2}{\hat{t}^2}\right]$
$gg \to gg$	$\frac{1}{2}\frac{1}{2\hat{s}}\frac{9}{2}\left(3-\frac{\hat{t}\hat{u}}{\hat{s}^2}-\frac{\hat{s}\hat{u}}{\hat{t}^2}-\frac{\hat{s}\hat{t}}{\hat{u}^2}\right)$

Jet production in hadron collisions

In the case of **2 -> 2** scattering, the process kinematics are specified by the **transverse momentum** of the outgoing partons and their rapidity. For **massless partons**

$$
\begin{aligned}
p_1 &= (p_T \cosh y_1, p_T \cos\phi, p_T \sin\phi, p_T \sinh y_1) \\
p_2 &= (p_T \cosh y_2, -p_T \cos\phi, -p_T \sin\phi, p_T \sinh y_2)
\end{aligned}
$$

Here $\mathbf{y_1}$ and $\mathbf{y_2}$ are the rapidities in the **laboratory** (hadronic center of mass) **frame**, different from the rapidities in the partonic center of mass frame (because of boost by PDFs)
Now momentum conservation implies that the **partonic Bjorken-x** are

$$
x_1 = \frac{p_T}{\sqrt{s}}\left(e^{y_1} + e^{y_2}\right) \qquad x_2 = \frac{p_T}{\sqrt{s}}\left(e^{-y_1} + e^{-y_2}\right)
$$

The partonic jet production matrix elements are computed in the **partonic center-of-mass frame,** so it is useful to express the kinematics in this frame

$$
y_1^* = -y_2^* \quad \to y_1^* = \frac{1}{2}(y_1 - y_2) = -y_2^*
$$

So the partonic center of mass frame **scattering angle** will be determined by

$$
\cos\theta^* = \tanh y_1^* = \tanh\left(\frac{y_1 - y_2}{2}\right)
$$

Difference in jet rapidities gives direct access to the partonic frame scattering dynamics

Jet production in hadron collisions

$$d\sigma^{\text{jet}} = \sum_{ijkl} dx_1\, dx_2\, f_i(x_1)\, f_j(x_2)\, \frac{d\hat{\sigma}_{ij\to kl}}{d\Phi_2}\, d\Phi_2$$

Now the jet cross-section in the $\mathbf{y_1}$, $\mathbf{y_2}$, $\mathbf{p_T}$ variables can be expressed as

$$\frac{d^3\,\sigma^{\text{jet}}}{dy_1\, d\,y_2 d\,p_T^2} = \frac{1}{16\pi\, s} \sum_{ijkl} dx_1\, dx_2\, \left(f_i(x_1)/x_1\right) \left(f_j(x_2)/x_2\right) \frac{d\hat{\sigma}_{ij\to kl}}{d\Phi_2} \frac{1}{1+\delta_{kl}}$$

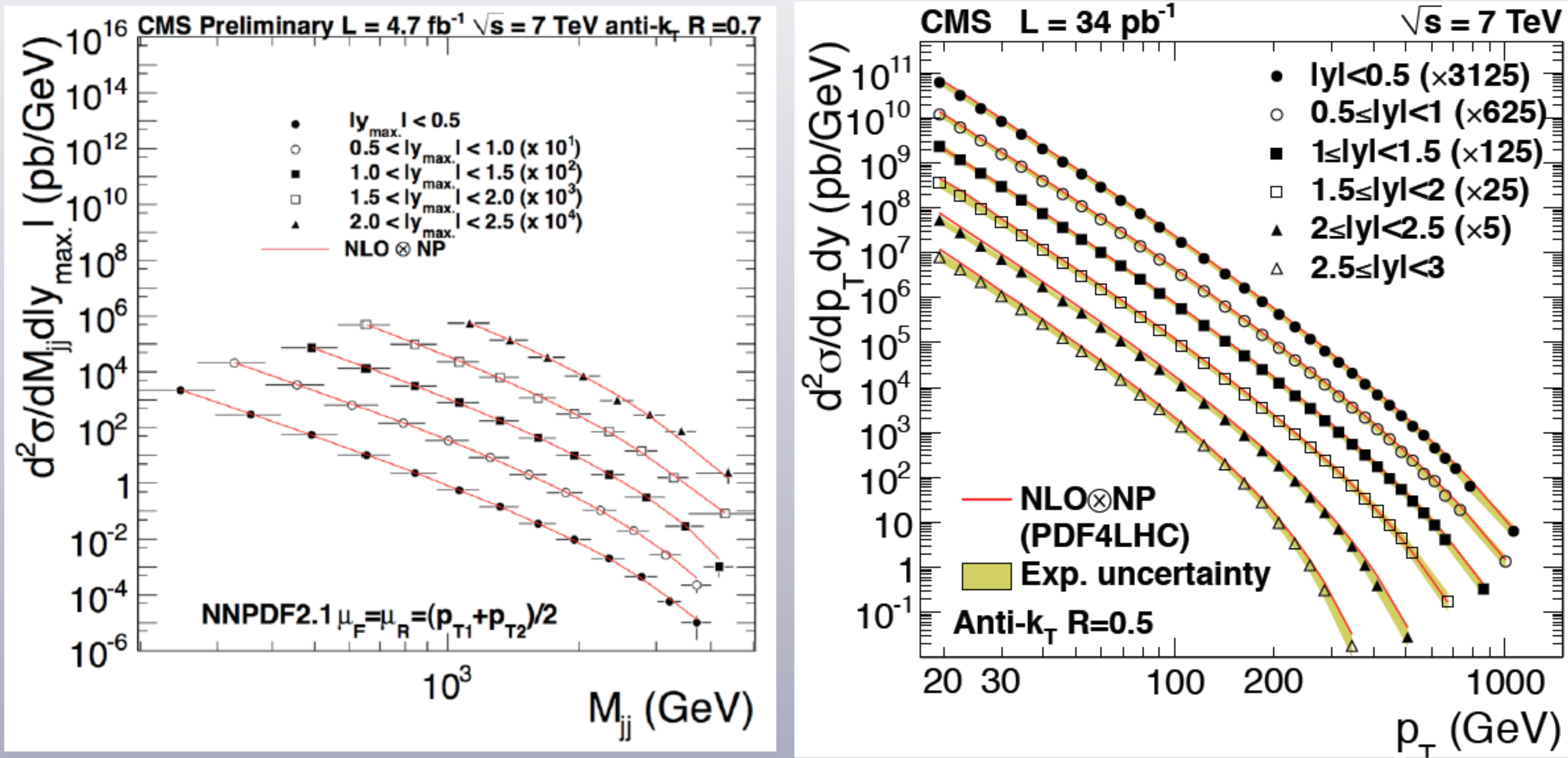
Note that this is the **Born processes,** to define jets in QCD at NLO level at beyond one needs to introduce a **jet algorithm**

An important variable is the **mass of the dijet system**

$$M_{12}^2 = (p_1 + p_2)^2 = 4\, p_T^2 \cosh^2 y^*\,, \quad M_{12} = 2\, p_T \cosh y^*$$

Inclusive jet and **dijet production** are being extensively studied at the LHC, both for Standard Model measurements as the **determination of the gluon PDF** and in **searches of new states of colored matter**

Jet production at the LHC: QCD



Inclusive jet and **dijet production** are key processes for the **determination of the gluon PDF** and of **the strong coupling constant**

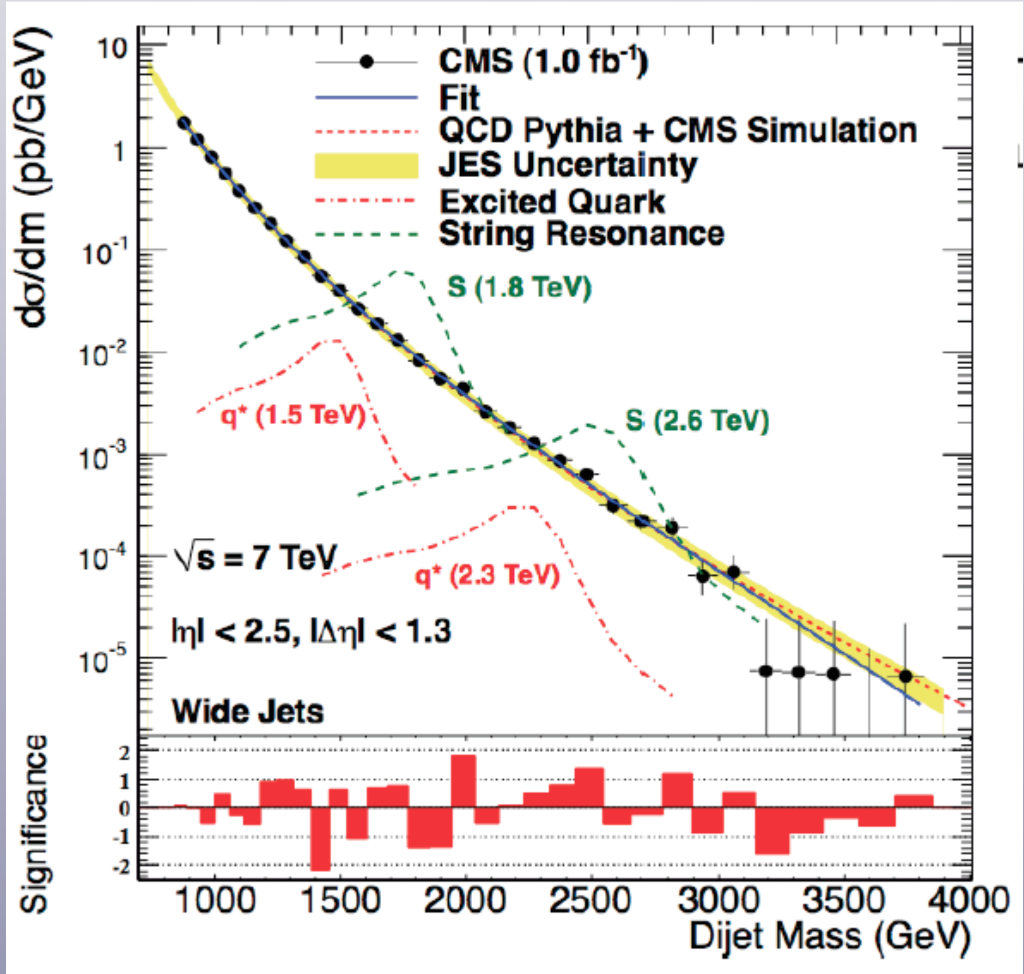
High Et jet data can **probe the running of the strong coupling up to the TeV regime** and put model independent limits on new colored matter

Jet production at the LHC: searches

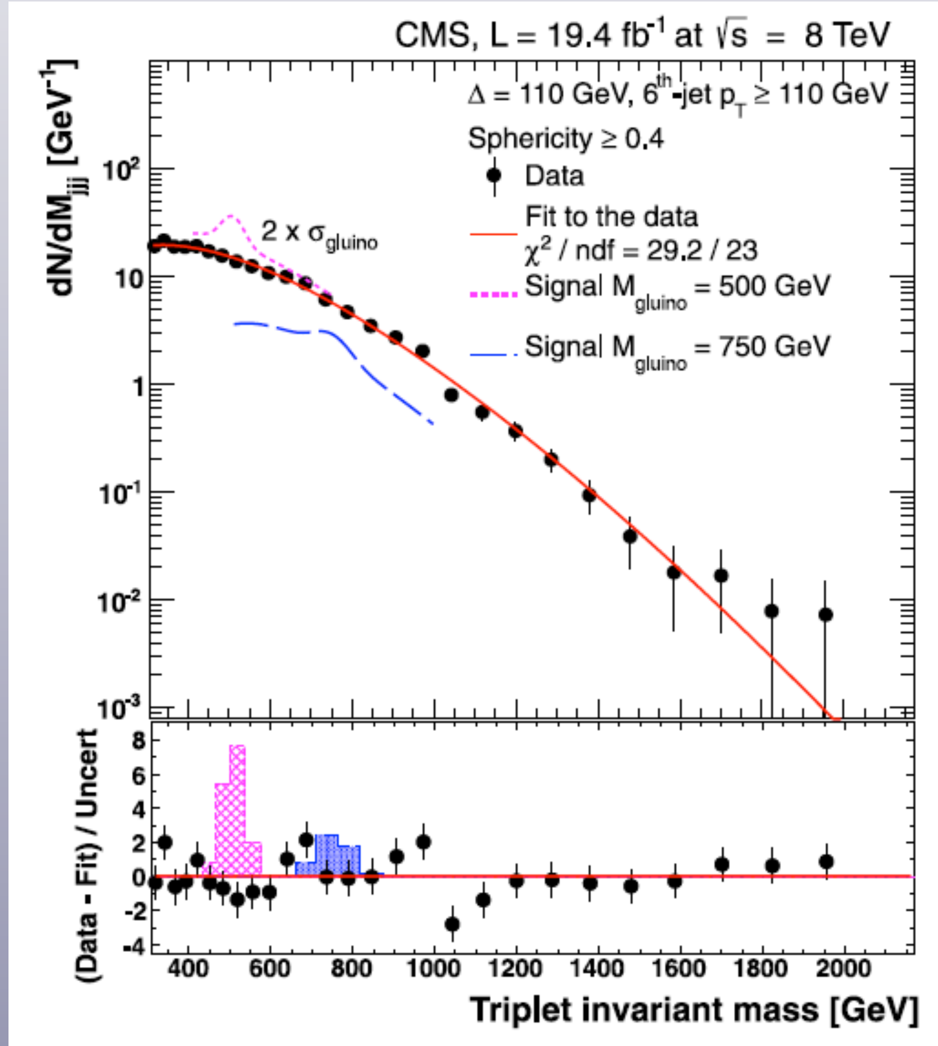
Searches for quark compositeness or **new colored resonances** have been performed in the two-jet, three-jet, four-jet, six-jet and even eight-jet final states

Search for excited quarks and string resonances in the dijet mass spectrum

Sensitivity up to 4 TeV



Search for gluino -> 3 jets in three jet final states



Jet production in hadron collisions

The numerically more relevant partonic channels are those in the **t-channel** (from the singularities die to exchange of massless vector bosons), for which

$$\frac{d^2\sigma^{\rm jet}}{dM_{12}d\cos\theta^*} = \sum_{ij}\int_0^1 dx_1 dx_2 f_i(x_1) f_j(x_2)\delta(x_1x_2 s - M_{12})\frac{d\hat{\sigma}}{d\cos\theta^*}$$

where the partonic cross-section has the usual **Rutherford scattering** form

$$\frac{d\hat{\sigma}}{d\cos\theta^*} \sim \frac{1}{\sin^4(\theta^*/2)}$$

The distribution is typically plotted against a **variable χ** defined to r**emove the Rutherford singularity**

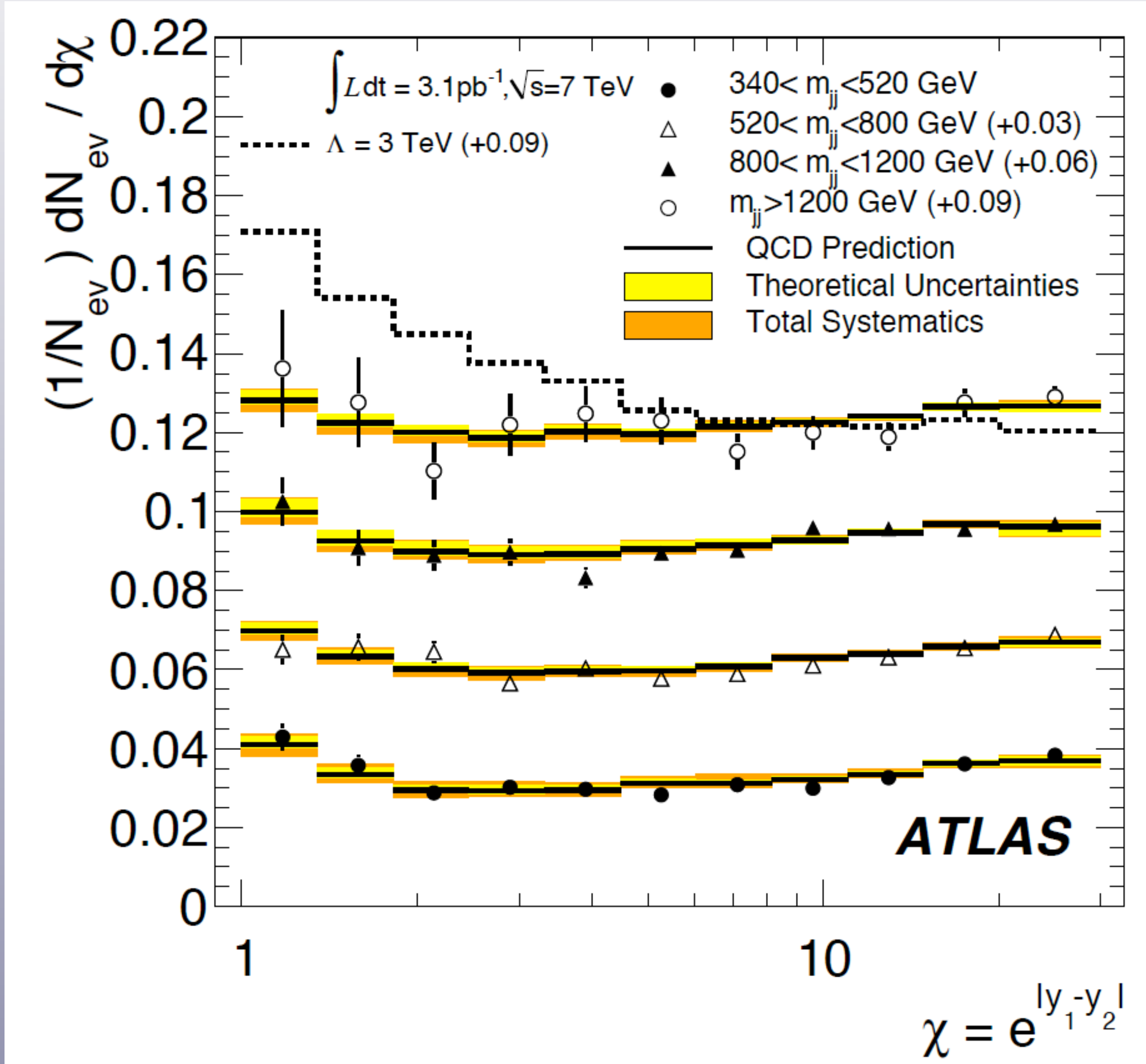
$$\chi \equiv \frac{1+\cos\theta^*}{1-\cos\theta^*} \qquad \frac{d\hat{\sigma}}{d\chi} \propto \text{constant}$$

Different models **other than QCD** will give very different results for this distribution
For instance in models where the **gluon is a scalar** we find

$$\frac{d\hat{\sigma}}{d\chi} \propto \frac{1}{(1+\chi)^2}$$

Jet production in hadron collisions

Clean channel to explore the **possible substructure of quarks** at the LHC



PDF luminosities

It is helpful in many cases to write the hadronic cross-section as a convolution of the partonic cross-section and a **partonic luminosity,** which encodes all the dependence on the PDFs

$$\tau \frac{dL_{ij}}{d\tau} = \frac{1}{1+\delta_{ij}} \int_0^1 dx_1 dx_2 \left[x_1 f_i(x_1,\mu) x_2 f_j(x_2,\mu) + (1 \to 2) \right] \delta(\tau - x_1 x_2)$$

Now, if the partonic cross-section depends only on $\hat{s} = x_1 x_2 s \equiv \tau s$

$$\sigma(s) = \sum_{ij} \int_{\tau_0}^1 \frac{d\tau}{\tau} \left[\frac{1}{s} \frac{dL_{ij}}{d\tau} \right] \left[\hat{s} \hat{\sigma}_{ij} \right]$$

So the hadronic cross-section can be evaluated as a product of the **PDF luminosity** and of the **reescaled partonic cross-section**

This expression is very useful to estimate event rates without doing the actual calculation

In many cases of interest, the partonic cross-section is dominated by the **threshold behaviour**

$$\sigma(s) \sim \sum_{ij} \int_{\tau_0}^1 \frac{d\tau}{\tau} \left[\frac{1}{s} \frac{dL_{ij}}{d\tau} \right] \left[\hat{s} \tilde{\sigma}_{ij} \delta(\hat{s} - m_x^2) \right] = \sum_{ij} \left[\frac{1}{s} \frac{dL_{ij}}{d\tau} (\tau = m_x^2/s) \right] \left[\tilde{\sigma}_{ij} (\hat{s} = m_x^2) \right]$$

Collider Reach

Already with this rudimentary introduction of **hadron collider physics,** it is possible to carry very interesting phenomenology estimates

A nice example is the **ColliderReach** project, by **G. Salam and A. Weiler,** that provides estimates for **the discovery/exclusion reach of future colliders** given existing bounds

http://collider-reach.web.cern.ch/collider-reach/

Basic idea is that hadronic cross-sections are **convolutions of PDF luminosities** and **partonic cross-sections**, with the appropriate mass factors included

$$\boxed{N(m,s) = \frac{1}{m^2}\sum_{ij} C_{ij}\,\mathcal{L}_{ij}(m^2,s)\,.}$$

$$\mathcal{L}_{ij}(m^2,s) = \int_\tau^1 \frac{dx}{x} x f_i(x,m^2)\,\frac{\tau}{x} f_j\left(\frac{\tau}{x},m^2\right) \qquad \tau \equiv \frac{m^2}{s}$$

When changing the collider center-of-mass energy, for fixed final state masses, the variation of the number of expected signal events dominated by the **PDF luminosity**

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$$\frac{N_{\text{signal-events}}(M^2_{\text{high}}, 14\,\text{TeV}, \text{Lumi})}{N_{\text{signal-events}}(M^2_{\text{low}},\ 8\,\text{TeV},\ 19\text{fb}^{-1})} = 1$$

Estimate the mass-reach of future colliders from **ratios of PDF luminosities**

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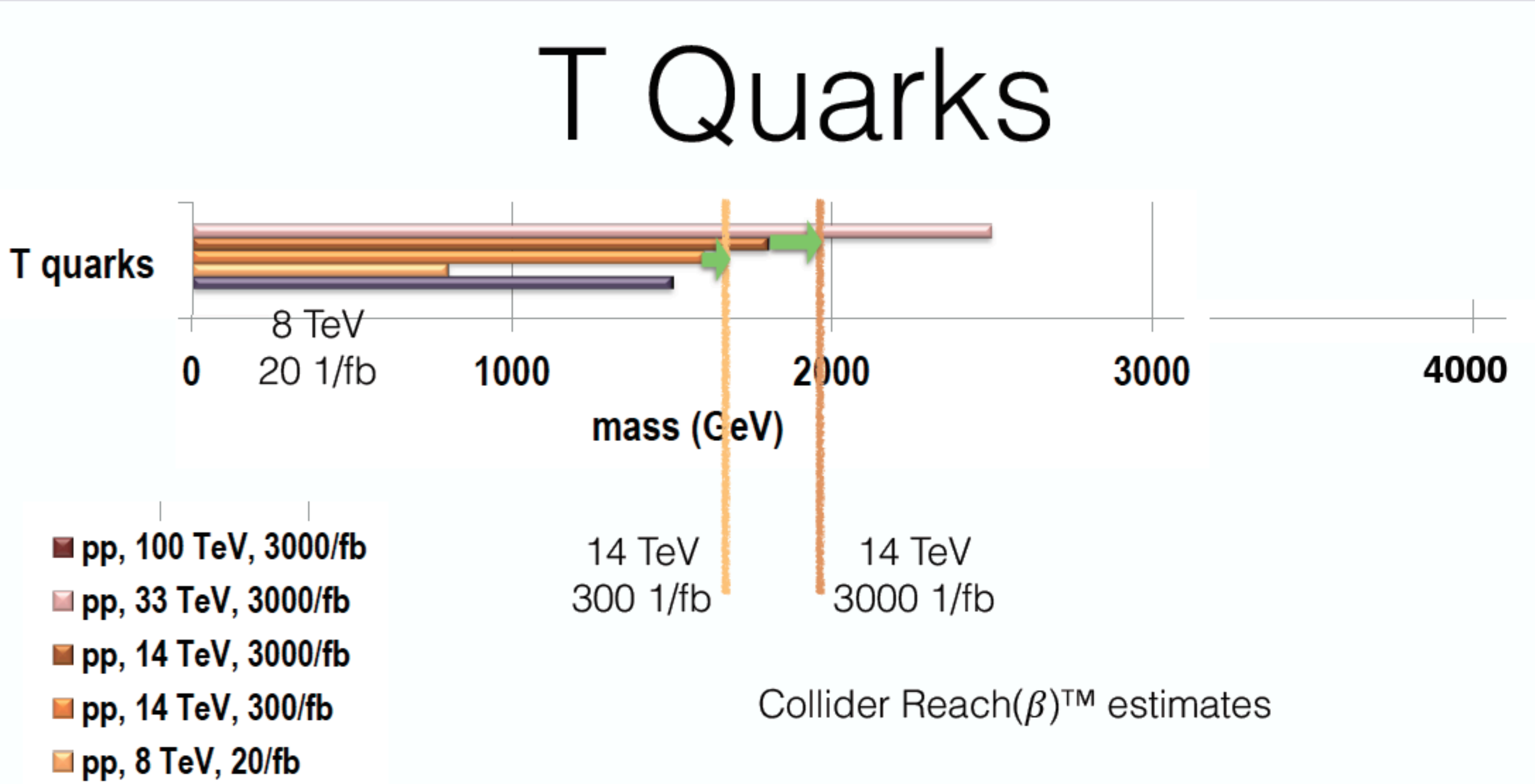

Simple **ColliderReach** estimates quite reasonable agreement with **full feasibility studies** including detector simulation, Monte Carlo event generation etc

Summary

In this lecture we studied the predictions of perturbative QCD in **hadron-hadron collisions**

- ☑ In hadron collisions, due to PDFs the hadron and parton center of mass frames do not coincide, it is advantageous to describe **kinematics with variables that are invariant under longitudinal boost** (transverse momentum) or that they **transform simply** (rapidities)
- ☑ We can use the parton model to, provided we extract the **Parton Distribution Functions** from other processes, perform robust predictions at the LHC (QCD factorization theorem)
- ☑One of the simplest yet more important processes at hadron colliders is **Drell-Yan production,** relevant for precision SM physics and for many BSM studies
- ☑ **Jet hadroproduction** is also an important process, both for QCD measurements like the gluon PDF and for a rich variety of BSM searches
- ☑ In this lecture we just scrapped the surface of hadron collider phenomenology: more in future lectures

However, in fixed-order calculations we can describe only **final states of reduced multiplicity**

Realistic LHC final states contain tens or hundreds of particles

We can use **perturbative QCD** to perform an **all-order resummation** of **soft and collinear emissions,** which are enhanced due to the singularities in the QCD matrix elements

This procedure is known as the **QCD parton shower,** and it is implemented in the widely used **Monte Carlo event generators**