Perturbative and colorful lectures on **Strong Interactions**

lecture 4/4

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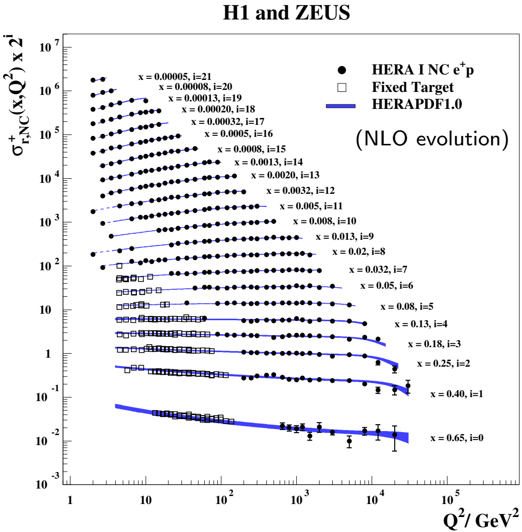
Belgian Dutch German summer school (BND 2022) - Callantsoog (NL)

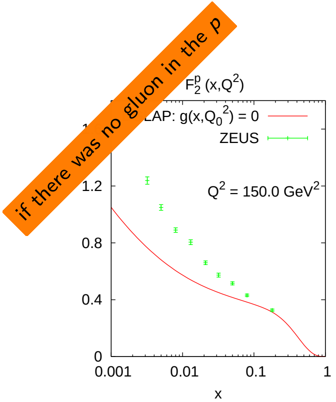
September 9, 2022

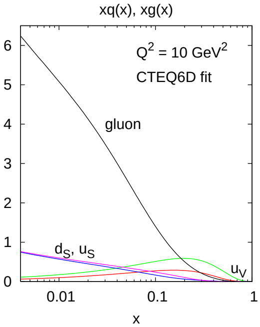
DIS: recap


H1 and ZEUS
HERA I NC e+p
Fixed Target
HERAPDF1.0
(NLO evolution)
x = 0.00005, i=21
x = 0.00008, i=20
x = 0.00013, i=19
x = 0.00020, i=18
x = 0.00032, i=17
x = 0.0005, i=16
x = 0.0008, i=15
x = 0.0013, i=14
x = 0.0020, i=13
x = 0.0032, i=12
x = 0.005, i=11
x = 0.008, i=10
x = 0.013, i=9
x = 0.02, i=8
x = 0.032, i=7
x = 0.05, i=6
x = 0.08, i=5
x = 0.13, i=4
x = 0.18, i=3
x = 0.25, i=2
x = 0.40, i=1
x = 0.65, i=0
σ+r,NC(x,Q2) x 2i
Q2/ GeV2

PDF evolutions: recap

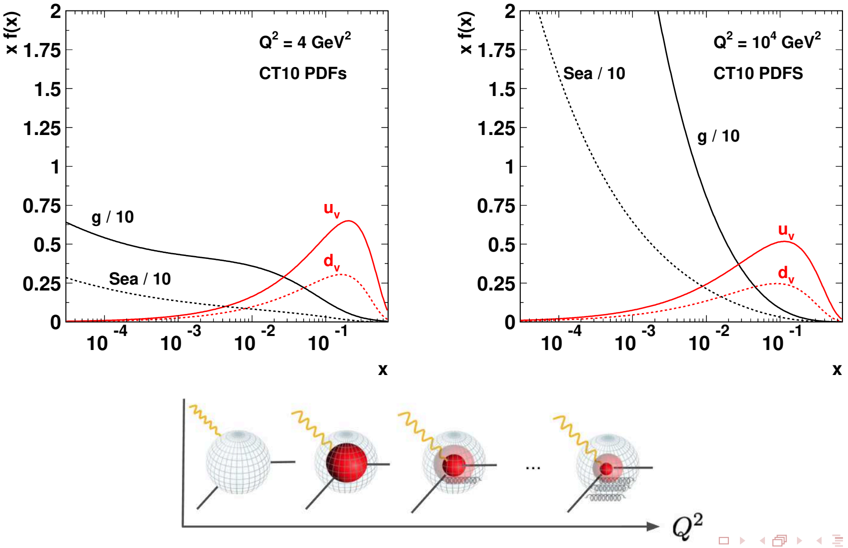
$$q(x,Q^2) = q(x,\mu_F^2) + \frac{\alpha_s}{2\pi}\int_x^1 \frac{d\xi}{\xi}\, q(\xi,\mu_F^2)\, P_{qq}\left(\frac{x}{\xi}\right) \ln\left(\frac{Q^2}{\mu_F^2}\right) + \frac{\alpha_s}{2\pi}\int_x^1 \frac{d\xi}{\xi}\, g(\xi,\mu_F^2)\, P_{qg}\left(\frac{x}{\xi}\right) \ln\left(\frac{Q^2}{\mu_F^2}\right)$$





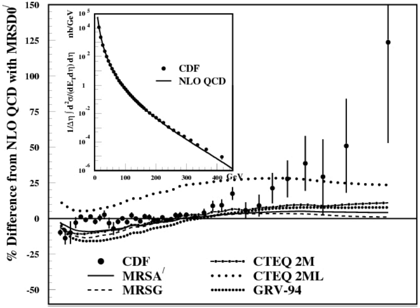
Gluon distribution is **HUGE!**

PDF evolutions: recap



PDF applied to other processes

extracted quark and gluon densities can then be used to predict other cross section like $p + \bar{p} \rightarrow 2\ jets$:



⇒ evidence for quark compositeness in 1995 at TeVatron

PDF applied to other processes

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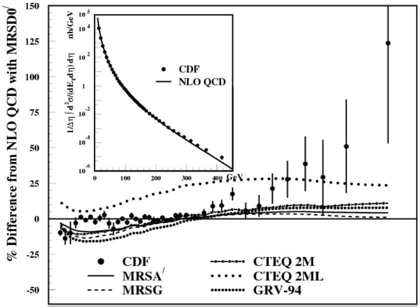
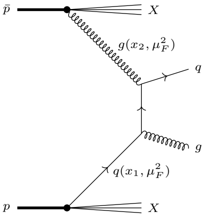




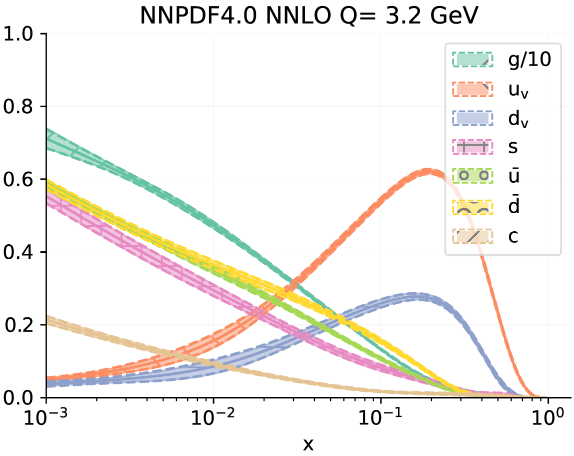
$\Rightarrow$ ~~evidence for quark compositeness in 1995 at TeVatron~~

No ! Wrong conclusion because **no PDF uncertainty** was delivered !

here important effect of gluon at large x

PDF uncertainties - state of the art

NNPDF4.0 [2022]

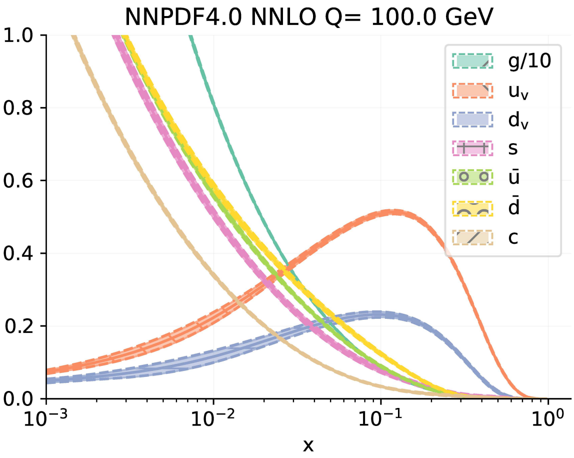


Major activity is translation of experimental errors (and theory uncertainties) into *uncertainty bands on extracted PDFs.*

PDFs with uncertainties allow one to estimate *degree of reliability* of future predictions

PDF uncertainties - state of the art

NNPDF4.0 [2022]



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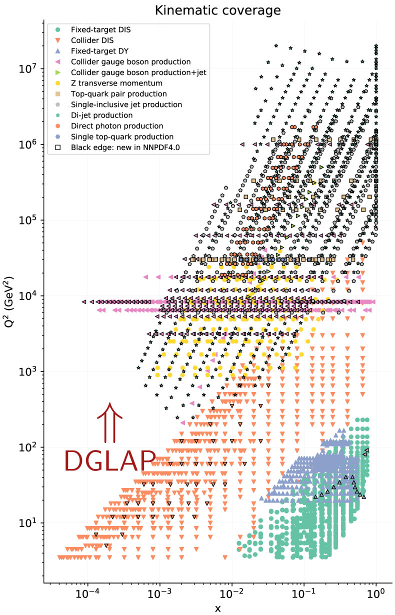
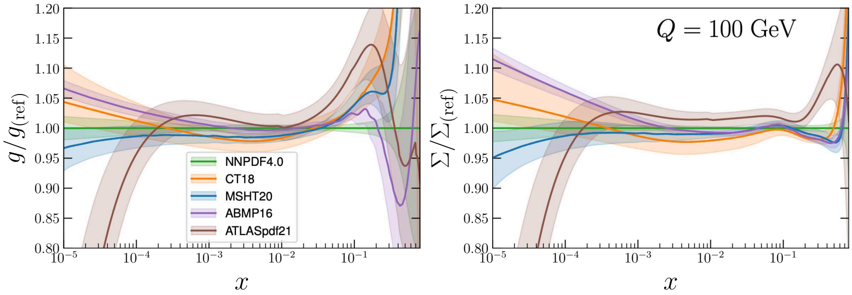


- combined fit of many different measurements (cross sections, ratios, ...) from different colliders & fix target
- most of the measurements for $x \geq 3\,10^{-4}$

Uncertainties



[arXiv:2203.13923]

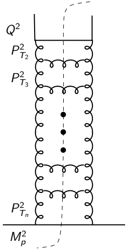
- different parametrisations compatible in the well measured phase space
- large differences in the extrapolation region ($x \leq 10^{-4}$)
- large uncertainty on g at $x > 0.1$ and for q at $x \to 1$

DGLAP

$$q(x,Q^2) = q(x,\mu_F^2) + \frac{\alpha_s}{2\pi}\int_x^1 \frac{d\xi}{\xi}\, q(\xi,\mu_F^2)\, P_{qq}\left(\frac{x}{\xi}\right) \ln\left(\frac{Q^2}{\mu_F^2}\right) + \frac{\alpha_s}{2\pi}\int_x^1 \frac{d\xi}{\xi}\, g(\xi,\mu_F^2)\, P_{qg}\left(\frac{x}{\xi}\right) \ln\left(\frac{Q^2}{\mu_F^2}\right)$$

This can interpreted as the first rung in a set of ladder diagrams, whose rungs are strongly ordered in $\ln Q^2$.

Including higher orders correponds to include more rungs in the ladder.



$Q^2 \simeq p^2_{T1} \gg p^2_{T2} \gg p^2_{T3} \gg \ldots$

$\Rightarrow$ DGLAP equations take into account all contributions propotional to:

$$[\alpha_S(Q^2)\ln(\frac{Q^2}{Q_0^2})]^n$$

At small x

$$P_{qq}(z) = \frac{C_F}{2\pi}\left[\frac{1+z^2}{(1-z)} + \frac{3}{2}(1-z)\right] \xrightarrow{z\to 0} cst$$

$$P_{gg}(z) = \frac{C_A}{\pi}\left[\frac{1}{z} + \frac{1}{(1-z)} - 2 + z(1-z)\right] \xrightarrow{z\to 0} 6/z$$

The DGLAP equation get simplified:

$$\frac{\partial xg(x,\mu^2)}{\partial \ln \mu^2} = \frac{3}{\pi b} xg(x,\mu^2)$$

(b includes the α_S dependence). Leads to a solution:

$$xg(x,\mu^2) \sim xg(x,\mu_0^2)\exp\left[2\sqrt{\frac{6}{b}\ln\ln(\frac{\mu^2}{\mu_0^2})\ln(\frac{1}{x})}\right]$$

i.e. double log approximation (DLA) to DGLAP.

⇒ Fast rise of the cross section at small x.

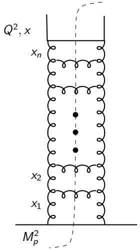
At still smaller x

$$\ln(\frac{1}{x}) \gg \ln(\frac{Q^2}{Q_0^2})$$

$\Rightarrow$ DGLAP not valid.

Need to consider gluon ladders with repeated iterations of $P_{gg}(z \ll 1)$ dominate, i.e. we have strong ordering in z.

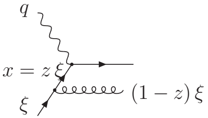
$x_1 \gg x_2 \gg x_3 \gg \ldots \gg x$



$\Rightarrow$ BFKL (Balitsky-Fadin-Kuraev-Lipatov) equations take into account all contributions propotional to:

$$[\alpha_S(Q^2)\ln(\frac{1}{x})]^n$$

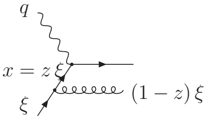
DGLAP/BFKL



$$\frac{\mathrm{d}\sigma}{\mathrm{d}p_T^2}(z) = \frac{4\pi^2\alpha e_q^2}{s}\frac{1}{p_T^2}\frac{\alpha_S}{2\pi}P_{qq}(z)$$

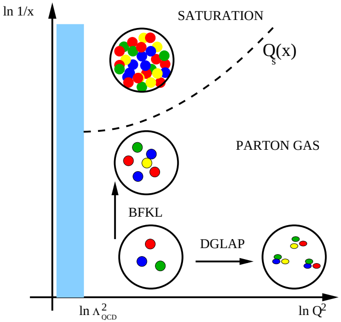
- $\int dP_T^2 \to \ln Q^2$: DGLAP

DGLAP/BFKL



$$\frac{d\sigma}{dp_T^2}(z) = \frac{4\pi^2\alpha e_q^2}{s}\frac{1}{p_T^2}\frac{\alpha_S}{2\pi}P_{qq}(z)$$

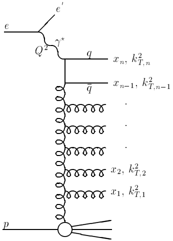
- $\int dP_T^2 \to \ln Q^2$: DGLAP
- $\int dz \to \ln 1/x$: BFKL

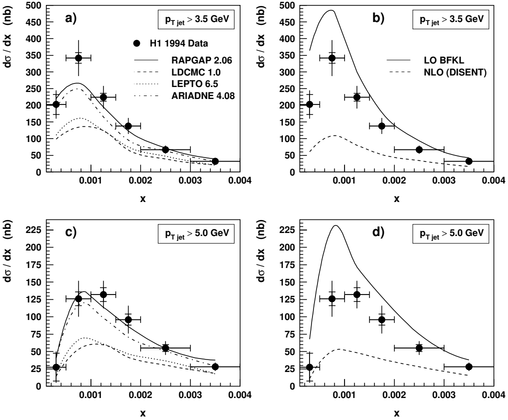


Forward jet production and BFKL

To try to find an evidence of the need of the BFKL dynamic: look at forward jet production.

Select events with $Q^2/P^2_{Tjet} \sim 1$ to supress DGLAP region of phase space.





- DGLAP (NLO) prediction too low
- BFKL closer to data

Saturation

Steep rise at small x is problematic: the density gets so large that re-interaction ($gg \to g$) should take place $\to$ saturation

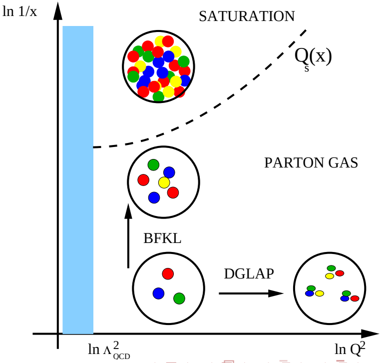
Saturation has to be expected when Q^2 is such than the recombination cross section times the number of gluons gets close to the hadron transverse size, i.e.

$$\sigma_{gg} N_g \simeq R_\perp$$

with $\sigma_{gg} \sim \alpha_S / Q^2$,
$N_g \sim xg(x, Q^2)$

saturation should start when:

$$Q_s^2(x) \sim \alpha_S \frac{xg(x,Q^2)}{R_\perp} \sim (\frac{1}{x})^\lambda$$

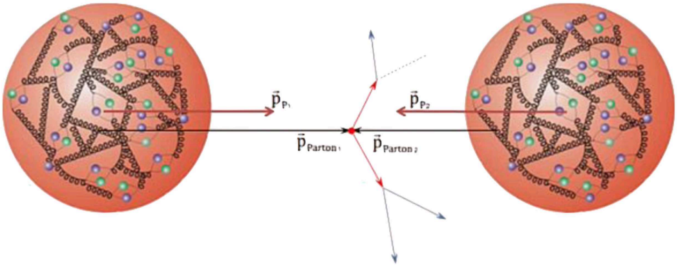


Conclusion of this section and open questions

- In a few decades our understanding of the proton structure has drastically changed
- from a static model with 3 valence quarks to a dynamic object with a high gluon density ($\rightarrow$ what is a colour field ?)
- DGLAP: phenomenal succes of pQCD on a large phase space (4x4 orders of magnetude)
- Do we have to go beyond DGLAP (BFKL dynamics, saturation,...) ? attractive explanations but not fully proven yet.
- many other open questions today:
  1) transverse spacial quark and gluon distributions ?
  2) correlations between partons ?
  3) how is the proton spin mad by the partons ? (orbital angulair momentum of q and g)
  4) ...

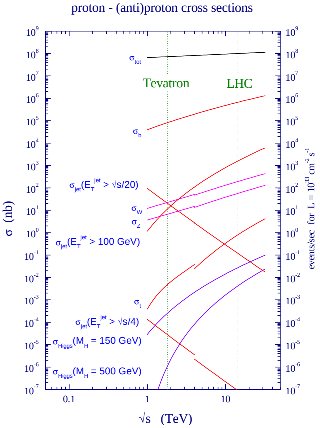
- Part 4 -

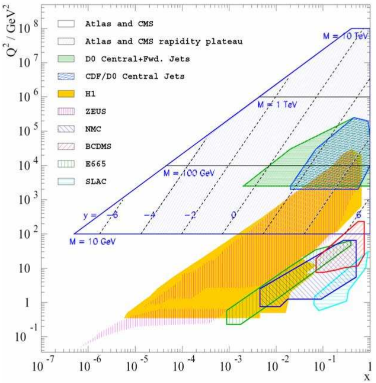
hadron - hadron interactions



High energy $p - p$ (or $p - \bar{p}$) interactions

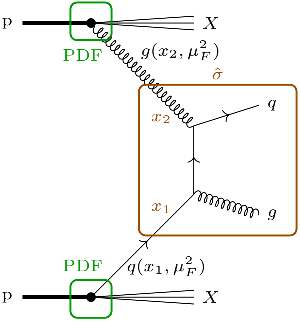
- most of the interactions are non perturbative - even at very high $\sqrt{s}$
- but the available energy makes high momentum transfer possible $\rightarrow$ perturbative interactions (scale $= Q^2$)



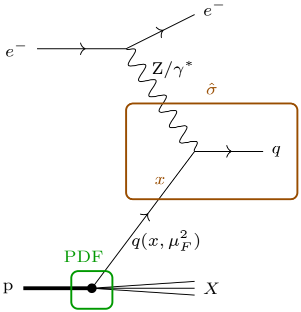


Cross section estimate: the master formula

hadron interactions



DIS



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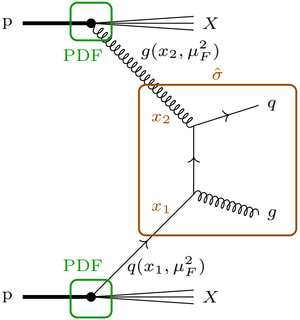
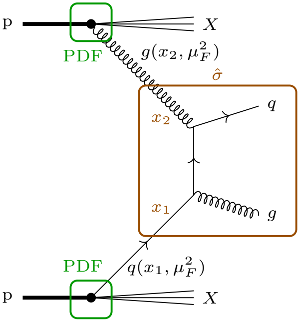


$$\sigma_{pp \to X(Q)} = \sum_{a,b=q,\bar{q},g} \int_0^1 dx_1\, dx_2\, f_{a/h}(x_1, \mu_F)\, f_{b/h'}(x_2, \mu_F)$$
$$\times\, \hat{\sigma}_{ab \to X(Q)}(x_1, x_2, Q, \mu_F, \alpha_s(\mu_R))$$
$$\times\, \theta(x_1 x_2\, s - Q^2)$$

Cross section estimate: the master formula



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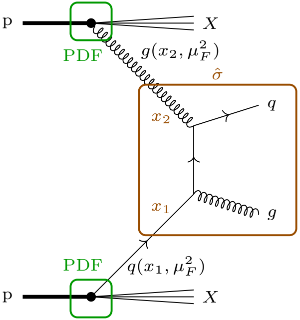
$$\times\; \theta(x_1 x_2\, s - Q^2)$$

$$\begin{aligned} Q^2 &= M_{qg}^2 = (p_q + p_g)^2 \\ &= 2\, E_q\, E_g\, (1 - \cos\theta_{qg}) \\ &= 4\, E_q\, E_g = 4\, x_1\, p_1\, x_2\, p_2 = x_1\, x_2\, s \end{aligned}$$

Cross section estimate: the master formula

hadron interactions



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$$\times\; \hat{\sigma}_{ab\to X(Q)}(x_1, x_2, Q, \mu_F, \alpha_s(\mu_R))$$
$$\times\; \theta(x_1 x_2\, s - Q^2) + \mathcal{O}\left(\frac{\Lambda^2_{QCD}}{Q^2}\right)$$

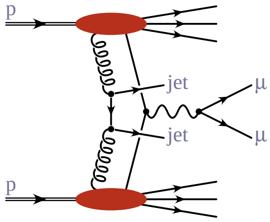
$\mathcal{O}\left(\frac{\Lambda^2_{QCD}}{Q^2}\right)$ vanishing term for $Q^2 \to \infty$

- that can break the factorisation
- called *higher twist*

Multiple Parton Interactions

high energy $\rightarrow$ high parton densities (at low x)
$\rightarrow$ probability of multiple partons scattering increases

Direct consequence of the composite nature of hadrons.
$\rightarrow$ Out of the frame of the QCD factorisation.
$\rightarrow$ No clear separation with single parton + splitting
$\rightarrow$ non-trivial changes of colour topology
$\rightarrow$ in case of two hard interactions: Double Parton Interaction (DPS)



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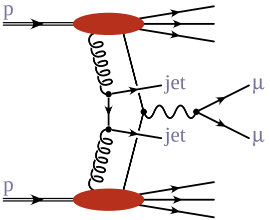
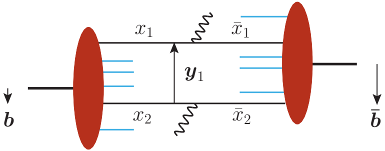


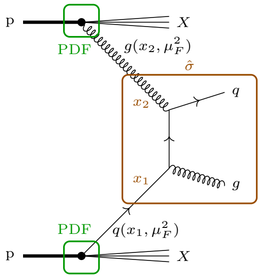
The correlation between the two partons depends on their relative distance:



$\Rightarrow$ possibility to learn about parton location in the proton (like GPDs ?).

Jet production

- The dijet (or total multijet) is the perturbative process with the highest cross section
- first test at a collider with higher energy to test QCD and the presence of new physics



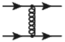
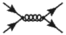
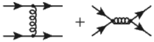
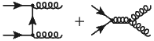
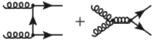
$$\frac{d^3\sigma}{dy_c\, dy_d\, dp_T^2} = \frac{1}{16\pi s^2 x_1 x_2} \sum_{a,b,c,d=q,\bar{q},g} f_{a/h}(x_1, \mu_F)\; f_{b/h'}(x_2, \mu_F) \times \overline{|\mathcal{M}(ab \to cd)|^2} \frac{1}{1+\delta_{cd}}$$

δ_{cd}: statistical factor for identical final state

- x_1 and x_2 can be accessed via:

$$\tau = \frac{\hat{s}}{s} = \frac{M_{cd}^2}{s} = x_1 x_2 \qquad y_{cd} = \frac{y_c + y_d}{2} = \frac{1}{2} \ln \frac{x_1}{x_2}$$

Dijet cross section calculation (LO)

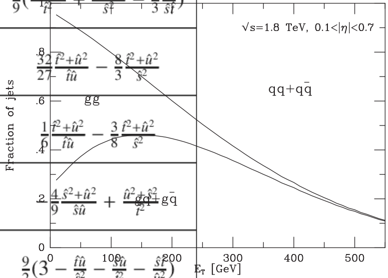
processus	diagrammes	$\overline{\lvert\mathcal{M}\rvert^2}/g^4$
$q\,q' \to q\,q'$		$\frac{4}{9}\frac{\hat{s}^2+\hat{u}^2}{\hat{t}^2}$
$q\,q \to q\,q$		$\frac{4}{9}\left(\frac{\hat{s}^2+\hat{u}^2}{\hat{t}^2}+\frac{\hat{s}^2+\hat{t}^2}{\hat{u}^2}\right)-\frac{8}{27}\frac{\hat{s}^2}{\hat{u}\hat{t}}$
$q\bar{q} \to q'\bar{q}'$		$\frac{4}{9}\frac{\hat{t}^2+\hat{u}^2}{\hat{s}^2}$
$q\bar{q} \to q\bar{q}$		$\frac{4}{9}\left(\frac{\hat{s}^2+\hat{u}^2}{\hat{t}^2}+\frac{\hat{t}^2+\hat{u}^2}{\hat{s}^2}-\frac{2}{3}\frac{\hat{u}^2}{\hat{s}\hat{t}}\right)$
$q\bar{q} \to gg$		$\frac{32}{27}\frac{\hat{t}^2+\hat{u}^2}{\hat{t}\hat{u}}-\frac{8}{3}\frac{\hat{t}^2+\hat{u}^2}{\hat{s}^2}$
$gg \to q\bar{q}$		$\frac{1}{6}\frac{\hat{t}^2+\hat{u}^2}{\hat{t}\hat{u}}-\frac{3}{8}\frac{\hat{t}^2+\hat{u}^2}{\hat{s}^2}$
$gq \to gq$		$-\frac{4}{9}\frac{\hat{s}^2+\hat{u}^2}{\hat{s}\hat{u}}+\frac{\hat{u}^2+\hat{s}^2}{\hat{t}^2}$
$gg \to gg$		$\frac{9}{2}\left(3-\frac{\hat{t}\hat{u}}{\hat{s}^2}-\frac{\hat{s}\hat{u}}{\hat{t}^2}-\frac{\hat{s}\hat{t}}{\hat{u}^2}\right)$

with

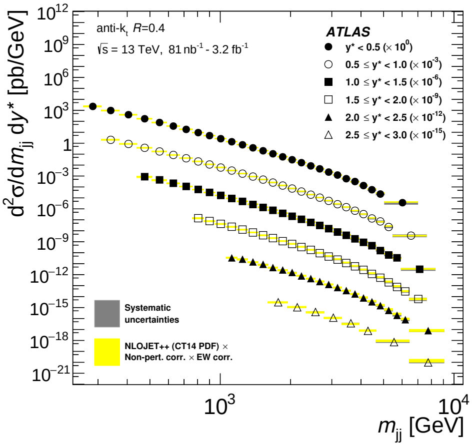
$\hat{s} = (p_a + p_b)^2$

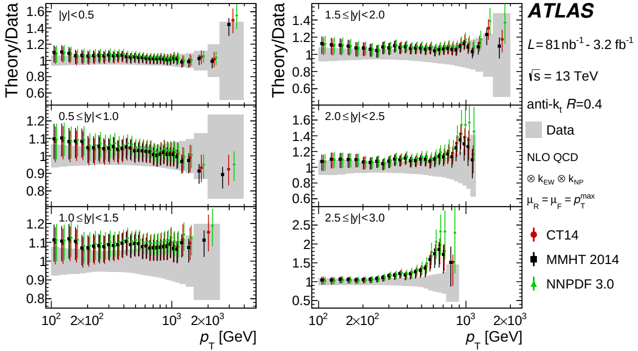
$\hat{t} = (p_a - p_c)^2$

$\hat{u} = (p_b - p_c)^2$



Dijet cross section measurement

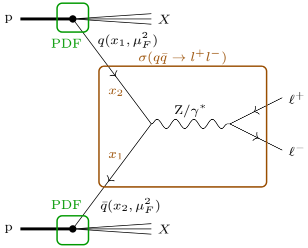




- this measurement constraints further gluon densities at large x

Drell-Yan process

- annihilation of a q with a $\bar{q}$ in hadronic interactions giving a charged lepton pair
- the only process in hadron interaction for which we are approaching percent level precision both experimentally and theoretically



at LO, on can derive easily $\sigma_{q\bar{q}\to l^- l^+}$ from:

$$\frac{d\sigma_{e^- e^+ \to q\bar{q}}}{d\Omega} = \frac{\alpha^2}{4s} e_q^2 \left(1 + \cos^2\theta\right) = \frac{\alpha^2}{4s} e_q^2 \frac{t^2 + u^2}{s^2}$$

where a sum on final state colors was done, here we should take the average:

$$\frac{d\sigma_{q\bar{q}\to l^- l^+}}{d\Omega} = \frac{1}{3} \frac{\alpha^2}{4s_{q\bar{q}}} e_q^2 \frac{t^2 + u^2}{s_{q\bar{q}}^2}$$

$$\sigma(q\bar{q} \to l^- l^+) = \frac{4\pi\alpha^2}{9 s_{q\bar{q}}} e_q^2$$

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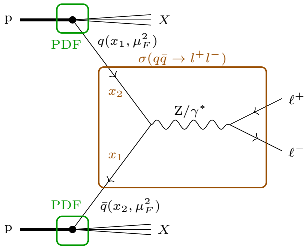


$$\frac{d\sigma_{pp\to l^- l^+ X}}{dQ^2} = \sum_{q,\bar{q}} \int_0^1 dx_1 \int_0^1 dx_2 \left[q(x_1)\bar{q}(x_2) + (q \leftrightarrow \bar{q})\right] \times \sigma(q\bar{q} \to e^- e^+)\, \delta(Q^2 - s_{q\bar{q}})$$

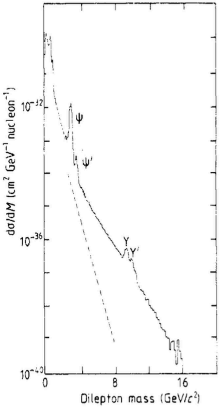
using $\tau = \frac{m_{ll}^2}{s} = \frac{Q^2}{s} = \frac{s_{q\bar{q}}}{s} = x_1 x_2$ and using the δ to get rid of the integral over x_2:

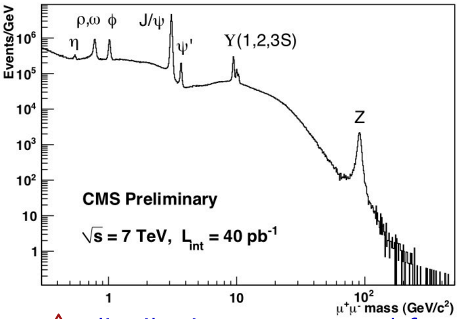
$$\frac{d\sigma_{pp\to l^- l^+ X}}{d\tau} = \frac{4\pi\alpha^2}{9s}\frac{1}{\tau} \sum_{q,\bar{q}} e_q^2 \int_\tau^1 \frac{dx_1}{x_1} \left[q(x_1)\bar{q}(\tau/x_1) + (q \leftrightarrow \bar{q})\right]$$

$\Rightarrow$ scaling (as in DIS)

DY: Mass distribution

- here we derived only the one γ exchange
- but resonances have to be taken into account
- in particular the Z boson at the LHC/TeVatron

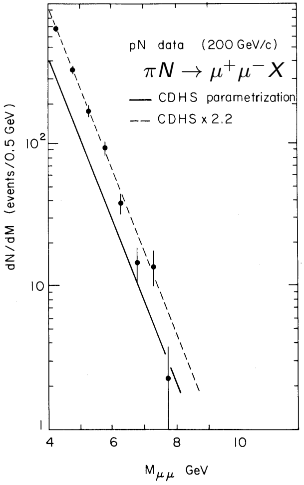


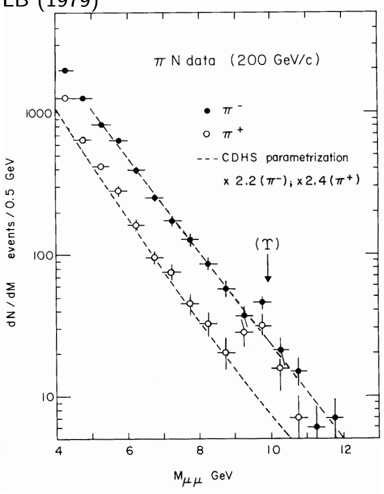


⚠ distribution not corrected for acceptance and efficiency effects !

First DY Cross section measurements

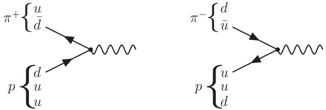
NA3 - PLB (1979)





- (out of the resonance regions) scaling observed ! confirms the model i.e. also the QCD factorisation

- $\frac{\sigma(\pi^- N \to \mu^+\mu^-)}{\sigma(\pi^+ N \to \mu^+\mu^-)} \simeq 2$ as expected



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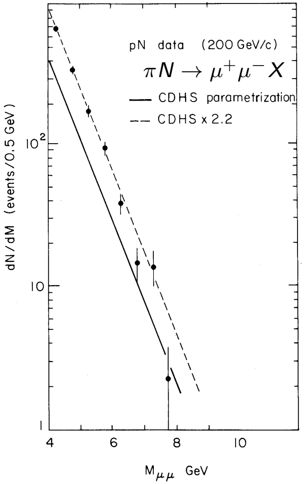

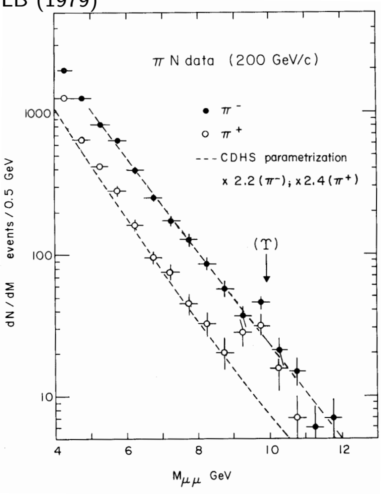

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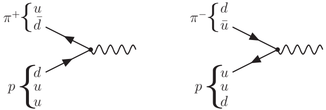


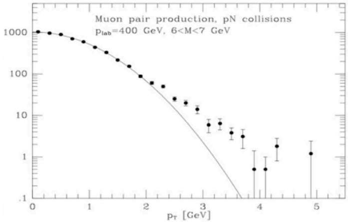
- but the normalisation is wrong by a factor 2.2 !

great success, but...

DY: transverse momentum

- in top of the normalisation problem, the transverse momentum of the lepton pair is not described

- at LO, everything is longitudinal (x of PDF are p longitudinal momentum fraction)



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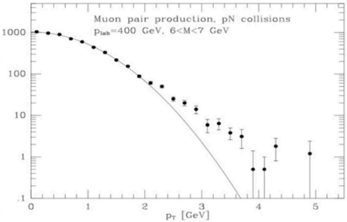


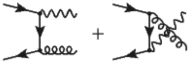
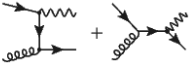
- at LO, everything is longitudinal (x of PDF are p longitudinal momentum fraction)

- low P_T part explained by the Fermi motion inside the proton:

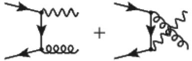
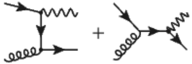
$\Delta p \geq \hbar/2\Delta x \simeq 113$ MeV for each transverse direction and each proton (of $\Delta x = 0.87$ fm)
$\Rightarrow$ typically 500 MeV (fit to date gives 760 MeV)

- missing NLO !

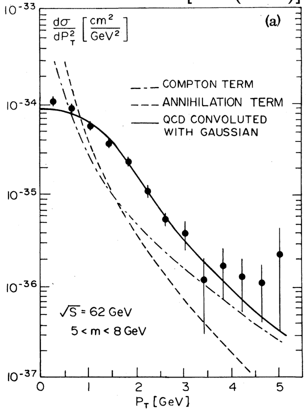
DY at NLO

LO	NLO	
	processus d'annihilation	processus QCD
$q + \bar{q} \to \gamma^*$	$q + \bar{q} \to g + \gamma^*$	$q + g \to q + \gamma^*$
		
1	$16\pi^2 \alpha_S \alpha \frac{8}{9}\left[\frac{\hat{u}^2}{\hat{t}^2} + \frac{\hat{t}^2}{\hat{u}^2} + \frac{2M^2\hat{s}}{\hat{u}\hat{t}}\right]$	$16\pi^2 \alpha_S \alpha \frac{1}{3}\left[-\frac{\hat{t}^2}{\hat{s}^2} - \frac{\hat{s}^2}{\hat{t}^2} - \frac{2M^2\hat{u}}{\hat{s}\hat{t}}\right]$

DY at NLO

LO	NLO	
	processus d'annihilation	processus QCD
$q+\bar{q}\to\gamma^*$	$q+\bar{q}\to g+\gamma^*$	$q+g\to q+\gamma^*$
		
1	$16\pi^2\alpha_S\alpha\frac{8}{9}\left[\frac{\hat{u}^2}{\hat{t}^2}+\frac{\hat{t}^2}{\hat{u}^2}+\frac{2M^2\hat{s}}{\hat{u}\hat{t}}\right]$	$16\pi^2\alpha_S\alpha\frac{1}{3}\left[-\frac{\hat{t}^2}{\hat{s}^2}-\frac{\hat{s}^2}{\hat{t}^2}-\frac{2M^2\hat{u}}{\hat{s}\hat{t}}\right]$

[ISR (1982)]



$\Rightarrow$ nicely describes the large P_T distribution

$\Rightarrow$ nicely describes the normalisation

- large NLO effect because a new type of diagram comes in, furthermore with (huge) gluon densities

complete success

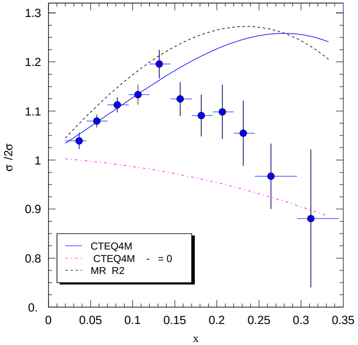
DY constrains on PDF

- assuming hypercharge symmetry such as $u = u_p = d_n$ and et $d = d_p = u_n$,
- assuming there are only 2 flavours :

$$\sigma^{pp} \sim \frac{4}{9}u(x_1)\bar{u}(x_2) + \frac{1}{9}d(x_1)\bar{d}(x_2)$$

$$\sigma^{pn} \sim \frac{4}{9}u(x_1)\bar{d}(x_2) + \frac{1}{9}d(x_1)\bar{u}(x_2)$$

[E866 (2001)]

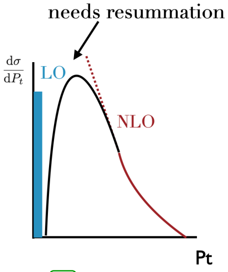


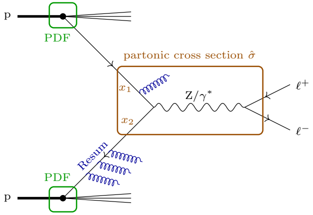
the ratio, using p and deuterium target:

$$\frac{\sigma^{pd}}{2\sigma^{pp}} = \frac{(1 + \frac{1}{4}\frac{d(x_1)}{u(x_1)})}{(1 + \frac{1}{4}\frac{d(x_1)}{u(x_1)}\frac{\bar{d}(x_2)}{\bar{u}(x_2)})}(1 + \frac{\bar{d}(x_2)}{\bar{u}(x_2)}) \simeq 1 + \frac{\bar{d}(x_2)}{\bar{u}(x_2)}$$

$\Rightarrow$ the sea distributions of $\bar{u}$ and $\bar{d}$ are different ! Surprise !

DY: state of the art

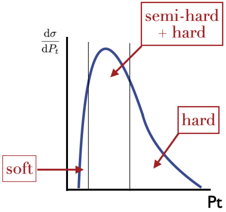




- the NLO contribution diverges at low P_t

- a realistic description of the P_t spectrum requires a resummation of many gluon radiation

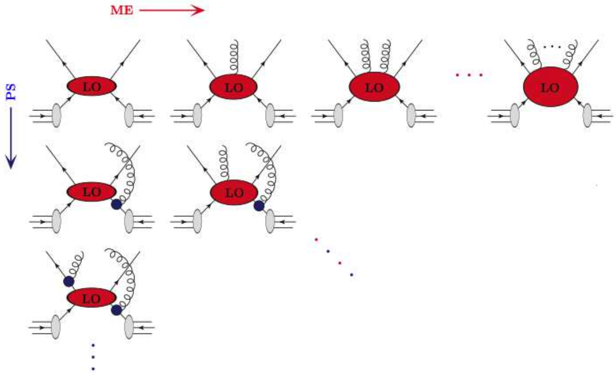
- can be done in different ways:
  - analytic calculation
  - Monte Carlo Parton Showers (PS)
  - PDF → Transverse Momentum Distributions (TMDs)



Multileg Monte Carlo

- to compute NN...NNLO is presently not possible

- several modern Monte Carlos make generate separated samples of LO ME for a given number of parton in the final state



- PS is added on each colored branch of each event

- globally: ME $\to$ large P_T, PS $\to$ small P_T

- merging procedure is done avoiding double counting

- samples are put together

- drawback: PS have fitted parameters they depend on $\sqrt{s}$ $\to$ problem somewhere !

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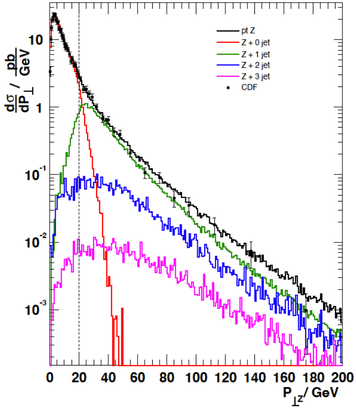
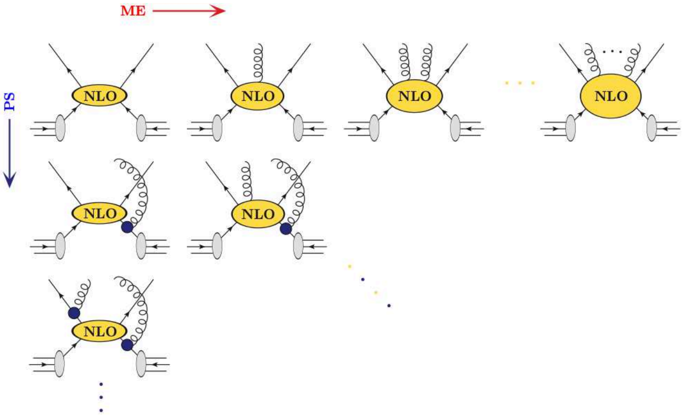
CDF [PRL 84 (2000)]

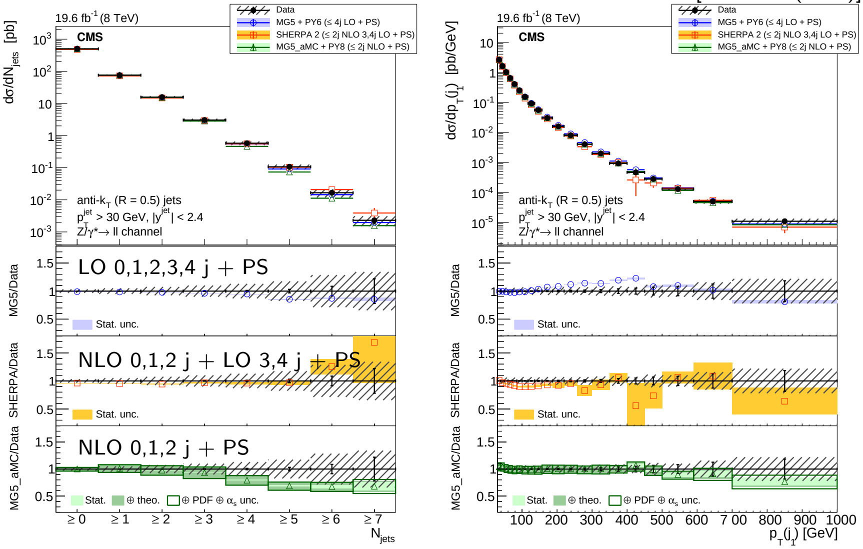


NLO multileg Monte Carlo

- some MC push the complexity to including NLO ME in a multileg approach:



CMS [JHEP 04 (2017)]



$Z + jet(s)$

- need ME with many partons to described high jet multiplicity
- need ME at NLO to describe well the P_t shapes (jet or Z), at large P_t
- approaching high precision, in a large phase space and for up to 2 jet multiplicities

TMDs: Transverse Momemtum Distributions

- PDF: $f_a(x, \mu^2)$ are purely longitudinal, $a = q, g$
- TMDs: $f_a(x, \vec{k_t}, \mu^2)$ include a transverse component
- $\exists$ several different approaches. Example here PB TMDS: *Parton Branching TMDs*

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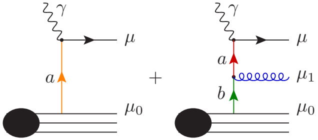
- $\exists$ several different approaches. Example here PB TMDS: *Parton Branching TMDs*
- idea of PB TMDS: construct iteratively $\vec{k_t}$ purely dynamically

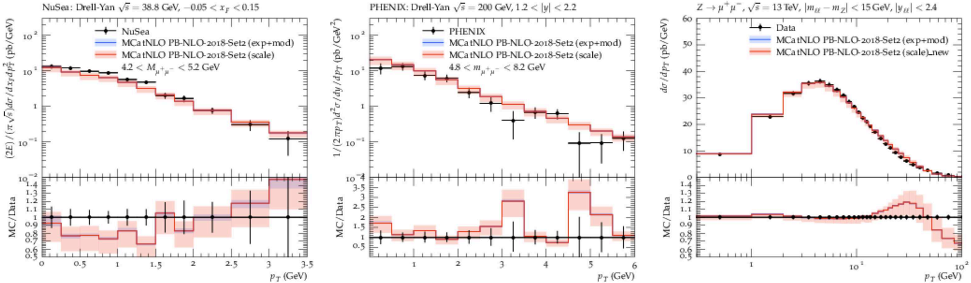
$$f_a(x,\mu^2) = f_a(x,\mu_0^2)\Delta_a(\mu^2,\mu_0^2)$$
$$+ \int_{\mu_0^2}^{\mu^2} \frac{d\mu_1^2}{\mu_1^2} \Delta_a(\mu^2,\mu_1^2) \sum_b \int_x^{z_M} \frac{dz}{z} \frac{\alpha_S}{2\pi} P_{ab}^R(z) f_b\left(x/z,\mu_1^2\right) \Delta_b(\mu_1^2,\mu_0^2)$$



$\Delta_a(\mu_2^2, \mu_1^2)$ is Sudakov form factor, i.e. the probability to have a scale evolution $\mu_1^2 \to \mu_2^2$) without parton radiation

PBTMDs

- an iterative procedure is applied, keeping in memory the kinematic at each step
- and in particular the transverse momenta, choosing: $p_T^2 = (1-z)^2 \mu_i^2$
- PBTMDs are obtained from fit to HERA data, then predicts Drell-Yan cross sections:



[Eur.Phys.J.C 80 (2020) 7, 598]

- only 1 parameter of non-pert. origin: intrinsic p_t

great success !

Conclusion and Open questions

- The TeVatron & LHC opened a new range in energy
- allowed study processes at high scales and multijet production
- huge progresses have been achieved on all aspects
- a precise prediction (at % level) remains a challenge for many observables
- they are needed to measure the Higgs production (very close to Drell-Yan) and decay as precisely as possible
- and to put constrains on new physics

General conclusions

- the understanding of the strong interactions has started about 50 years ago
- the strong interaction is responsible for a very large diversity of phenomena and reactions (confinement of hadrons and of nuclei, nuclear physics, asymptotic freedom, q-g plasma, particle interactions,...)
- we now reach the 1 percent precision level for some processes
- there are still many things to be understood and probably many surprises to come...