Hadron collider phenomenology

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INT Seattle  15 September 2010
hadron collider phenomenology is a very broad topic

I had to make drastic choices

I focused on some aspects of high $Q^2$ physics at **CDF, D0, ATLAS, CMS**
Standard Model

Past & Present: the LEP/SLD/Tevatron legacy

The Standard Model has been a spectacular success, weathering out all challenges

The comparison with the electroweak precision measurements has not changed much in the last years
Top quark production

CDF cross section is
$\sigma = 7.50 \pm 0.48 \text{ pb}$
relative uncertainty is
$\Delta \sigma / \sigma = 6.4\%$

D0 cross section is
$\sigma = 8.18^{+0.98}_{-0.87} \text{ pb}$
but with a smaller sample ($\sim 1 \text{ pb}^{-1}$)

CDF & D0 cross sections not combined yet; likely this winter
Top quark Mass

**Tevatron**

Run I: $178.0 \pm 4.3$ GeV

Run I + II: $173.3 \pm 1.1$ GeV

$\frac{\Delta m}{m} = 0.6\%$

**Theory**

$\frac{\Delta m}{m} = 0.2 \frac{\Delta \sigma}{\sigma}$

$\frac{\Delta \sigma}{\sigma} = 6\% \quad \rightarrow \quad \Delta m = 2$ GeV

the EXP error is $\Delta m = 1$ GeV

so the TH $\sigma$ should be known at 3% level
W boson Mass

Moriond 10

- CDF Run 0/I: $80.436 \pm 0.081$
- D0 Run I: $80.478 \pm 0.083$
- CDF Run II: $80.413 \pm 0.048$
- Tevatron 2007: $80.432 \pm 0.039$
- D0 Run II: $80.402 \pm 0.043$
- Tevatron 2009: $80.420 \pm 0.031$
- LEP2 average: $80.376 \pm 0.033$
- World average: $80.399 \pm 0.023$

D0’s is world best measurement

| | \[ \frac{\Delta m_W}{m_W} = 0.03\% \] |

not changed much over last years

- Tevatron average more precise than LEP’s
- D0 measurement based on 500k W’s
- ATLAS, CMS will collect each as many W’s after \( \sim 200 \text{ pb}^{-1} \)
Effects on global EW fits

Electroweak fits point to a light Higgs boson

Tree level

$$m_W = m_Z \cos \theta_W$$

One loop

$$m_W^2 \left( 1 - \frac{m_W^2}{m_Z^2} \right) = \frac{\pi \alpha}{\sqrt{2} G_F} (1 + \Delta r)$$

$$\Delta r_t = - \frac{3\alpha \cos^2 \theta_W}{16\pi \sin^4 \theta_W} \frac{m_t^2}{m_W^2}$$

$$\Delta r_H = \frac{11\alpha}{48\pi \sin^2 \theta_W} \ln \frac{m_H^2}{m_W^2}$$

Reducing the top mass error

$$\delta m_t = 1 \text{ GeV} \Rightarrow \delta m_W(m_t) = 6 \text{ MeV}$$

so

$$\delta m_W \propto m_t^2$$

$$\delta m_W \propto \ln m_H$$
Higgs search at Tevatron

Tevatron Run II Preliminary, $L=2.0-5.4$ fb$^{-1}$

95% CL Limit/SM

LEP Exclusion

Tevatron Exclusion

$N_{NLO}$

$NLO$

LO

$m_H$(GeV/c$^2$)
use $m_t$ to estimate $m_H$ from EW corrections

as $m_t$ changes, large shifts in $m_H$

$m_H > 114.4$ GeV from direct search at LEP

$m_H = 87^{+36}_{-27}$ GeV from EW fits

At 95% CL

$m_H < 160$ GeV from EW fits

$m_H < 190$ GeV combined with direct search at LEP
the Standard Model is in excellent shape, but ...

- **ElectroWeak Symmetry Breaking** not tested
- neutrino masses and mixings not included
- dark matter ?
- baryogenesis ?

foremost task of the LHC is to understand the **EWSB**: find the **Higgs** boson or whatever else is the cause of it
**LHC**

- **pp** \( \sqrt{s} = 14 \text{ TeV} \) \( L_{\text{design}} = 10^{34} \text{ cm}^{-2} \text{ s}^{-1} \) (after 2013)
- **pp** \( \sqrt{s} = 7 \text{ TeV} \) \( L_{\text{initial}} \leq 10^{33} \text{ cm}^{-2} \text{ s}^{-1} \) (2010-2011)
- Heavy ions (e.g. Pb-Pb at \( \sqrt{s} \sim 1000 \text{ TeV} \))

---

**TOTEM** (integrated with CMS):
- pp, cross-section, diffractive physics

**ATLAS and CMS**:
- General purpose

**27 km LEP ring**
- 1232 superconducting dipoles \( B=8.3 \text{ T} \)

**ALICE**:
- ion-ion, p-ion

**LHCb**:
- pp, B-physics, CP-violation

**Here**: ATLAS and CMS
LHC at present (end of August 2010)

average luminosity $7.08 \times 10^{30}$ cm$^{-2}$ s$^{-1}$

peak luminosity $1.07 \times 10^{31}$ cm$^{-2}$ s$^{-1}$

to be increased by a factor $10$ ($100$) by end of 2010 (2011)

integrated luminosity $3.7$ pb$^{-1}$

(but $1.7$ pb$^{-1}$ collected in the last week of running)
LHC at design energy and luminosity

the LHC will be a SM factory with (perhaps) lots of New Physics signals

design luminosity
\[ L = 10^{34} \text{ cm}^{-2} \text{ s}^{-1} = 10^{-5} \text{ fb}^{-1} \text{ s}^{-1} \]

integrated luminosity (per year)
\[ L \approx 100 \text{ fb}^{-1} \text{ yr}^{-1} \]
With 1 fb\(^{-1}\) at 14 TeV we shall get

<table>
<thead>
<tr>
<th>final state</th>
<th>events</th>
<th>overall # of events</th>
</tr>
</thead>
<tbody>
<tr>
<td>jets ((p_T &gt; 100 \text{ GeV}))</td>
<td>(10^9)</td>
<td></td>
</tr>
<tr>
<td>jets ((p_T &gt; 1 \text{ TeV}))</td>
<td>(10^4)</td>
<td></td>
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<tr>
<td>(W \to e\nu, \mu\nu)</td>
<td>(2 \cdot 10^7)</td>
<td>(10^7) (Tevatron)</td>
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<tr>
<td>(Z \to \ell\ell)</td>
<td>(2 \cdot 10^6)</td>
<td>(10^6) (LEP)</td>
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<tr>
<td>(b\bar{b})</td>
<td>(5 \cdot 10^{11})</td>
<td>(10^9) (BaBar, Belle)</td>
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<tr>
<td>(t\bar{t})</td>
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Even at 1 fb\(^{-1}\) luminosity, LHC beats all the other accelerators at 7 TeV, figures are slightly reduced:

- \(W\) x-sect goes from 20 nb at 14 TeV to 10 nb at 7 TeV
- \(tt\) x-sect goes from 850 pb at 14 TeV to 450 pb at 7 TeV
Even at 7 TeV, LHC is a copious source of SM processes, in particular lots of $W, Z, \text{top, jets}$.
**LHC**: present & future

- Calibrate the detectors, and re-discover the SM i.e. measure known cross sections: jets, W, Z, tt

- Understand the EWSB/find New-Physics signals (ranging from Z’ to leptons, to gluinos in SUSY decay chains, to finding the Higgs boson)

- Constrain and model the New-Physics theories

- In all the steps above (except probably Z’ to leptons) precise QCD predictions play a crucial role
SM Higgs at the LHC at 7 TeV

How do the production rates change when going from Tevatron to the LHC at 7 TeV?

Higgs: mainly $gg$ fusion → gain a factor $\sim 15$
SM Higgs at the LHC at 7 TeV

LHCC meeting of 5/05/10

depending on the analysis technique, discovery at 3 to 5 $\sigma$ at $m_H \sim 160$ GeV
SM Higgs at the LHC at 7 TeV

1 fb⁻¹

Exclusion: One experiment only

CMS Preliminary: projection for 7 TeV 1 fb⁻¹

Mar 17 2010

Higgs mass, \( m_H [\text{GeV}/c^2] \)

\( r = \sigma_{95\% CL}/\sigma_{SM} \)

95\% CL exclusion: mean
95\% CL exclusion: 68\% band
95\% CL exclusion: 95\% band
95\% CL exclusion: mean (no sys)

exclusion range ~ 145 - 190 GeV
SM Higgs at the LHC at 14 TeV

... of course production rates are much bigger at 14 TeV with an adequate luminosity

however, when energy and luminosity are fixed, the issue is to estimate accurately the significance

i.e. to compute accurately signal and background production rates

background = W, Z, top + n jets

an accurate estimate of the background is the hardest thing to do

more on that later
MSSM neutral Higgs at the LHC at 7 TeV

LHCC meeting of 5/05/10

- discovery (exclusion) down to $\tan \beta \sim 20$ (15) at low $m_A$
- with 1 fb$^{-1}$ at 7 TeV, LHC overtakes Tevatron at 10 fb$^{-1}$ on all Higgs searches
New Physics at the **LHC at 7 TeV**

squarks at $m \sim 350$ GeV
assume production like for top
85% $qq + 15\%$ $gg$
$0.85 \times 10 + 0.15 \times 1000$
$\rightarrow$ gain a factor $\sim 150 - 200$

$Z'$ at $m \sim 1$ TeV
$qq$ production
$\rightarrow$ gain a factor $\sim 50$
New Physics at the LHC at 7 TeV

don’t have time to cover the many New Physics production channels (please see the minutes of the LHCC meeting of 5/05/10) it suffices to say that with 1 fb⁻¹ at 7 TeV:

for SUSY, LHC will be able to discover squarks with 500 GeV < m < 1 TeV,

for dilepton resonances (Z'), sensitivity (discovery/exclusion) up to 1.5 TeV, (with 100 pb⁻¹ up to 1 TeV)

and a long list of exotica (compositeness, Randall-Sundrum gravitons, excited leptons, 4ᵗʰ generation quarks, large extra dimension monojets and photon pairs ...) can be probed with 0.1 - 1 fb⁻¹
New Physics caveat: tales from the past - I

Jets at high transverse energy

CDF Collab. PRL 77 (1996) 438

excess of data over theory

Could it be contact interactions?

⇒ New Physics?

more prosaic explanation:

gluon density at high $x$ was largely unknown;
use Tevatron 2-jet data to measure it:
no more excess
New Physics caveat: tales from the past - II

B production in the 90’s

discrepancy between Tevatron data and NLO prediction
B cross section in $p\bar{p}$ collisions at 1.96 TeV

$$d\sigma(p\bar{p} \rightarrow H_bX, H_b \rightarrow J/\psi X)/dp_T(J/\psi)$$

**FONLL = NLO + NLL**

Cacciari, Frixione, Mangano, Nason, Ridolfi 2003

use of updated fragmentation functions by Cacciari & Nason and resummation

**Total cross section is** $19.4 \pm 0.3 (\text{stat})^{+2.1}_{-1.9} (\text{syst})$ nb

CDF hep-ex/0412071

**Good agreement with data**

no New Physics

Thursday, September 30, 2010
W, Z at the LHC at 7 TeV

With a few pb$^{-1}$

ATLAS, CMS have collected a few thousand W's so far.

Here is the cross section with 0.2 pb$^{-1}$ presented at ICHEP 2010.
W charge asymmetry at Tevatron

from the parton model

\[ \sigma(W^+) \propto u(x_1)\bar{d}(x_2) \quad \sigma(W^-) \propto d(x_1)\bar{u}(x_2) \]

because the \textit{ubar} distribution in the antiproton is the same as the \textit{u} distribution in the proton, at Tevatron \( \sigma(W^+) = \sigma(W^-) \)

however the \textit{u}'s carry more proton momentum than the \textit{d}'s, so the quantity

\[ A(y_W) = \frac{d\sigma(W^+)}{dy_W} - \frac{d\sigma(W^-)}{dy_W} \]

\[ = \frac{d\sigma(W^+)}{dy_W} + \frac{d\sigma(W^-)}{dy_W} \]

called charge asymmetry, is non zero

it has been measured by CDF & D0
$W^+/W^-$ at the LHC

At LHC there is no $W$ charge asymmetry: it’s $pp \rightarrow$ an even function of $y_W$ however, $u$ distribution is larger than $d$ \[ \sigma(W^+) > \sigma(W^-) \] the ratio \[ R^\pm = \frac{\sigma(W^+ \rightarrow e^+\bar{\nu})}{\sigma(W^- \rightarrow e^-\nu)} = \frac{u(x_1)d(x_2)}{d(x_1)\bar{u}(x_2)} \] is larger than 1

Kom Stirling 2010

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$R$ grows with $x$, so it decreases with $\sqrt{s}$

$R$ has
- small EXP systematics
- (N)NLO QCD corrections of $\leq 2$
- PDF uncertainty $\sim 1$-2%, driven by valence $u(x)/d(x)$ at not-so-small $x$
$W^+/W^-$ at the LHC

At LHC there is no $W$ charge asymmetry: it’s $pp \rightarrow \text{an even function of } y_W$

however, $u$ distribution is larger than $d$

$\sigma(W^+) > \sigma(W^-)$

the ratio

$$R^\pm = \frac{\sigma(W^+ \rightarrow \ell^+ \bar{\nu})}{\sigma(W^- \rightarrow \ell^- \nu)} = \frac{u(x_1)d(x_2)}{d(x_1)\bar{u}(x_2)}$$

is larger than 1

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Thursday, September 30, 2010
\[ \frac{W^+}{W^-} + n \text{ jets at the LHC} \]

assuming that we know the \( u/d \) ratio precisely, fixing

\[ \sigma_{\text{SM}} = \sigma_{\text{SM}}(W^+ + \text{jets}) + \sigma_{\text{SM}}(W^- + \text{jets}) \]

includes \( tt \) and \( H \) production, which are \( W \) symmetric assuming

\[ \sigma_{\text{NP}}(W^+ + \text{jets}) = \sigma_{\text{NP}}(W^- + \text{jets}) \]

the ratio

\[ R^\pm(n) = \frac{\sigma(W^+ \rightarrow n \text{ jets})}{\sigma(W^- \rightarrow n \text{ jets})} \]

probes \textbf{New Physics} in \( W + \text{jets} \)

\[ f_{\text{NP}} = \frac{\sigma_{\text{NP}}}{\sigma_{\text{SM}}} = \frac{2(R^\pm_{\text{SM}} - R^\pm_{\text{exp}})}{(R^\pm_{\text{SM}} + 1)(R^\pm_{\text{exp}} + 1)} \]

\( R^\pm_{\text{exp}} \) measured ratio

\( R \) grows with \( x \), which grows with \( n \)

however, note that \( R \) first decreases from \( n=0 \) to \( 1 \) then increases for \( n > 1 \) ...
**W^+ / W^- + n jets at the LHC**

Possible dynamic explanation: dominance of BFKL-like configuration for \( n > 1 \)

- In any scattering process with \( s >> t \), gluon exchange dominates.

- For \( s >> t \), BFKL resums the (next-to-)leading logarithmic contributions, \( \ln(s/t) \), to the radiative corrections to gluon exchange in the \( t \) channel.

- In \( W + \) jets, gluon exchange occurs with at least 2 jets.

- The dominant subprocess is \( q + g \rightarrow q + W^\pm + ng \).

- The leading-order subprocess breakdown is:

<table>
<thead>
<tr>
<th>( n )</th>
<th>( QQ )</th>
<th>( Qg )</th>
<th>( gg )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>100</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>18</td>
<td>82</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>21</td>
<td>73</td>
<td>6</td>
</tr>
<tr>
<td>3</td>
<td>23</td>
<td>70</td>
<td>7</td>
</tr>
<tr>
<td>4</td>
<td>25</td>
<td>67</td>
<td>8</td>
</tr>
</tbody>
</table>

- The issue can be further analysed using NLO production, known up to \( W + 4 \) jets.

- Berger *et al.* (BlackHat) 2010

- Andersen VDD Maltoni Stirling 2001
Top at the LHC at 7 TeV

top at \( m \sim 170 \text{ GeV} \)
85% \( qq \) + 15% \( gg \)
0.85 \( \times \) 5 + 0.15 \( \times \) 100
\( \rightarrow \) gain a factor \( \sim 20 \)
Top at the LHC at 7 TeV

With ~ 100 pb$^{-1}$, LHC sample comparable to Tevatron's

With ~ a few hundred pb$^{-1}$, physics programme will look familiar
- top cross section
- top mass
- single top
- rare decays

If LHC reaches 1 fb$^{-1}$ by end 2011, and Tevatron increases yield by a factor 10, samples will still be comparable
Radiative corrections at the LHC

*En passant*, we have mentioned higher order corrections in

- **Higgs** exclusion limit
- background to **Higgs** production
- jets at high transverse energy
- **b, t** production

**SM** production of **W, Z, t + jets** is background to **Higgs, New Physics** processes

**SUSY** decay chain

signal: missing energy + 4 jets

background: **Z (→νν)** + 4 jets
## NLO cross sections: experimenter’s wishlist

### 2005 Les Houches

Table 42: The LHC “priority” wishlist for which a NLO computation seems now feasible.

<table>
<thead>
<tr>
<th>process ((V \in {Z, W, \gamma}))</th>
<th>relevant for</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. (pp \to VV) (V) jet</td>
<td>(t\bar{t}H), new physics</td>
</tr>
<tr>
<td>2. (pp \to t\bar{t}bb)</td>
<td>(t\bar{t}H)</td>
</tr>
<tr>
<td>3. (pp \to t\bar{t} + 2) jets</td>
<td>(t\bar{t}H)</td>
</tr>
<tr>
<td>4. (pp \to VVbb)</td>
<td>(\text{VBF} \to H \to VV, t\bar{t}H,) new physics</td>
</tr>
<tr>
<td>5. (pp \to VV + 2) jets</td>
<td>(\text{VBF} \to H \to VV)</td>
</tr>
<tr>
<td>6. (pp \to V + 3) jets</td>
<td>various new physics signatures</td>
</tr>
<tr>
<td>7. (pp \to VVV)</td>
<td>SUSY trilepton</td>
</tr>
</tbody>
</table>
QCD at high $Q^2$

- Parton model
- Perturbative QCD
  - factorisation
  - universality of IR behaviour
  - cancellation of IR singularities
  - IR safe observables: inclusive rates
    - jets
    - event shapes
World average of $\alpha_s(M_Z)$

$$\alpha_s(M_Z) = 0.1184 \pm 0.0007$$

$$\frac{\Delta \alpha_s}{\alpha_s} = 0.6\%$$

vertical line and shaded band mark the world average for the first time that shapes are included at NNLO

S. Bethke arXiv:0908.1135
Factorisation

is the separation between the short- and the long-range interactions

\[
\sigma_X = \sum_{a,b} \int_0^1 dx_1 dx_2 f_{a/A}(x_1, \mu_F^2) f_{b/B}(x_2, \mu_F^2)
\]
\[
\times \hat{\sigma}_{ab \to X} \left(x_1, x_2, \{p_i^\mu\}; \alpha_S(\mu_R^2), \alpha(\mu_F^2), \frac{Q^2}{\mu_R^2}, \frac{Q^2}{\mu_F^2}\right)
\]

\[X = W, Z, H, Q\bar{Q}, \text{high-}E_T\text{jets, ...}\]

\(\hat{\sigma}\) is known as a fixed-order expansion in \(\alpha_S\)

\[
\hat{\sigma}(\alpha_S, \mu_R, \mu_F) = (\alpha_S(\mu_R))^n \left[\hat{\sigma}^{(0)} + \left(\frac{\alpha_S}{2\pi}\right) \hat{\sigma}^{(1)}(\mu_R, \mu_F) + \left(\frac{\alpha_S}{2\pi}\right)^2 \hat{\sigma}^{(2)}(\mu_R, \mu_F) + \ldots\right]
\]

\[\hat{\sigma}^{(0)} = \text{LO} \quad \hat{\sigma}^{(1)} = \text{NLO} \quad \hat{\sigma}^{(2)} = \text{NNLO}\]

\textbf{LO:} maximal dependence on scales. Poor convergence of expansion in \(\alpha_S\)

\textbf{NLO:} (usually) good estimate of x-sect

\textbf{NNLO:} good estimate of uncertainty
Factorisation

is the separation between the short- and the long-range interactions

\[ \sigma_X = \sum_{a,b} \int_0^1 dx_1 dx_2 f_{a/A}(x_1, \mu_R^2) f_{b/B}(x_2, \mu_R^2) \]

\[ \times \hat{\sigma}_{ab \to X} \left( x_1, x_2, \{ p_i^\mu \}; \alpha_s(\mu_R^2), \alpha(\mu_F^2), \frac{Q^2}{\mu_R^2}, \frac{Q^2}{\mu_F^2} \right) \]

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\textbf{LO:} maximal dependence on scales. Poor convergence of expansion in \( \alpha_s \)

\textbf{NLO:} (usually) good estimate of x-sect

\textbf{NNLO:} good estimate of uncertainty

extracted from data evolved through DGLAP

\( \hat{\sigma} \) is the separation between

\( P_a \)

\( P_b \)

\( X \)
Factorisation

is the separation between the short- and the long-range interactions

\[ \sigma_X = \sum_{a,b} \int_0^1 dx_1 dx_2 f_{a/A}(x_1, \mu_F^2) f_{b/B}(x_2, \mu_F^2) \times \hat{\sigma}_{ab \rightarrow X} \left( x_1, x_2, \{p_i^\mu\}; \alpha_S(\mu_R^2), \alpha(\mu_F^2), \frac{Q^2}{\mu_R^2}, \frac{Q^2}{\mu_F^2} \right) \]

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\( \hat{\sigma} \) is known as a fixed-order expansion in \( \alpha_S \)

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\text{LO: maximal dependence on scales. Poor convergence of expansion in } \alpha_S \text{ }
\text{NLO: (usually) good estimate of x-sect } \text{ }
\text{NNLO: good estimate of uncertainty }
Factorisation-breaking contributions

- underlying event
- power corrections
  - MC’s and theory modelling of power corrections laid out and tested at LEP where they provide an accurate determination of $\alpha_s$
  - models still need be tested in hadron collisions (see e.g. Tevatron studies at different $\sqrt{s}$)
- diffractive events
- double-parton scattering
  - observed by Tevatron CDF in the inclusive sample
    $$p\bar{p} \rightarrow \gamma + 3 \text{ jets}$$
  - potentially important at LHC
    $$\sigma_D \propto \sigma_S^2$$
- breakdown in dijet production at N$^3$LO?
Power corrections at Tevatron

Ratio of inclusive jet cross sections at 630 and 1800 GeV

\[ \sigma(630 \text{ GeV})/\sigma(1800 \text{ GeV}), \text{ with:} \]

\[ \sigma(\sqrt{s}) = \sigma(\sqrt{s})_{\text{NLO}} \left( E_T \to E_T + \Lambda \right) \]

in the theory curves

Solid: \( \Lambda = 2.8 \text{ GeV} \)

Dashes: \( \Lambda = 0 \)

\( \times \): CDF

Bjorken-scaling variable

\[ x_T = \frac{2E_T}{\sqrt{s}} \]

In the ratio the dependence on the pdf’s cancels

dashes: theory prediction with no power corrections

solid: best fit to data with free power-correction parameter \( \Lambda \) in the theory
Factorisation in diffraction ??

- Diffraction in DIS
- Double pomeron exchange in $p\bar{p}$
- No proof of factorisation in diffractive events
- Data do not seem to support it
PDF evolution

- Factorisation scale $\mu_F$ is arbitrary
- Cross section cannot depend on $\mu_F$
  \[ \mu_F \frac{d\sigma}{d\mu_F} = 0 \]
- Implies DGLAP equations
  \[ \mu_F \frac{df_a(x, \mu_F^2)}{d\mu_F} = P_{ab}(x, \alpha_S(\mu_F^2)) \otimes f_b(x, \mu_F^2) + O\left(\frac{1}{Q^2}\right) \]
  \[ \mu_F \frac{d\hat{\sigma}_{ab}(Q^2/\mu_F^2, \alpha_S(\mu_F^2))}{d\mu_F} = -P_{ac}(x, \alpha_S(\mu_F^2)) \otimes \hat{\sigma}_{cb}(Q^2/\mu_F^2, \alpha_S(\mu_F^2)) + O\left(\frac{1}{Q^2}\right) \]
- $P_{ab}(x, \alpha_S(\mu_F^2))$ is calculable in $pQCD$
LHC kinematic reach

LHC opens up a new kinematic range

$x$ range covered by HERA but $Q^2$ range must be provided by DGLAP evolution

100-200 GeV physics is large $x$ physics (valence quarks) at Tevatron, but smaller $x$ physics (gluons & sea quarks) at the LHC

rapidity distributions span widest $x$ range

Feynman $x$’s for the production of a particle of mass $M$

$$x_{1,2} = \frac{M}{14 \text{ TeV}} e^{\pm y}$$
### Parton cross section

#### 3 complementary approaches to $\hat{\sigma}$

<table>
<thead>
<tr>
<th></th>
<th>matrix-elem MC’s</th>
<th>fixed-order x-sect</th>
<th>shower MC’s</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>final-state description</strong></td>
<td>hard-parton jets.</td>
<td>limited access to final-state structure</td>
<td>full information available at the hadron level</td>
</tr>
<tr>
<td></td>
<td>Describes geometry, correlations, ...</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>higher-order effects: loop corrections</strong></td>
<td>hard to implement: must introduce negative probabilities</td>
<td>straightforward to implement (when available)</td>
<td>included as vertex corrections (Sudakov FF’s)</td>
</tr>
<tr>
<td><strong>higher-order effects: hard emissions</strong></td>
<td>included, up to high orders (multijets)</td>
<td>straightforward to implement (when available)</td>
<td>approximate, incomplete phase space at large angles</td>
</tr>
<tr>
<td><strong>resummation of large logs</strong></td>
<td>?</td>
<td>feasible (when available)</td>
<td>unitarity implementation (i.e. correct shapes but not total rates)</td>
</tr>
</tbody>
</table>

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M.L. Mangano KITP collider conf 2004

Thursday, September 30, 2010
Parton shower **MonteCarlo** generators

- **HERWIG**  B. Webber *et al.* 1992  
  re-written as a C++ code (HERWIG++)

- **PYTHIA**  T. Sjostrand 1994  (also re-written as a C++ code)

- **SHERPA**  F. Krauss *et al.* 2003  
  model parton showering and hadronisation

**LHC Event Simulation**
Matrix-element MonteCarlo generators

- several automated codes to yield large number of (up to 8-9) final-state partons
- can be straightforwardly interfaced to parton-shower MC’s
- ideal to scout new territory

- large dependence on ren/fact scales
  example: Higgs (via gluon fusion) + 2 jets is $\alpha_s^4(Q^2)$
  → unreliable for precision calculations
Matrix-element MonteCarlo generators

multi-parton LO generation: processes with many jets (or V/H bosons)

- **ALPGEN**  M.L. Mangano M. Moretti F. Piccinini R. Pittau A. Polosa 2002
- **COMPHEP**  A. Pukhov et al. 1999
- **GRACE/GR@PPA**  T. Ishikawa et al. K. Sato et al. 1992/2001
- **HELAC**  C. Papadopoulos et al. 2000

processes with 6 final-state fermions

- **PHASE**  E. Accomando A. Ballestrero E. Maina 2004

merged with parton showers

- all of the above, merged with HERWIG or PYTHIA
MonteCarlo interfaces

**CKKW**  S. Catani F. Krauss R. Kuhn B. Webber 2001

**MLM**  L. Lonnblad 2002  M.L. Mangano 2005

procedures to interface parton subprocesses with a different number of final states to parton-shower MC’s

**MC@NLO**  S. Frixione B. Webber 2002

**POWHEG**  P. Nason 2004

procedures to interface NLO computations to parton-shower MC’s

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Single top in **MC@NLO**

Frixione Laenen Motylinski Webber 2005

at low $p_T$, parton shower models collinear radiation

at high $p_T$, NLO models hard radiation

---

Thursday, September 30, 2010
Matrix-element MonteCarlo generator at NLO

desirable to have a multi-parton NLO generator interfaced to a parton shower:
a sort of MadGraph cum MC@NLO

a step in this direction: automation of subtraction of IR divergences

MadGraph provides real amplitude
user inputs virtual amplitude
procedure provides subtraction counterterms

Frederix Frixione Maltoni Stelzer 2009
Accuracy of pQCD calculations

- LO $2 \rightarrow 2$ process + shower & hadronisation (HERWIG, PYTHIA, SHERPA)
- LO $2 \rightarrow n$ process + shower (ALPGEN, MADGRAPH/MADEVENT)
- NLO parton level
- NLO + shower (MC@NLO, POWHEG)
- NNLO parton level

bottom line: use best available accuracy (ideally NLO + shower)
High (EXP) demand for cross sections of $X + n$ jets
$X = W, Z, \text{Higgs, heavy quark(s)}, ...$
Big TH community effort

To compute the NLO cross section of $X + n$ jets, we need:
1) tree-level amplitude for $X + (n+3)$ partons
2) one-loop amplitude for $X + (n+2)$ partons
3) a method to cancel the IR divergences
   and so to compute the cross section

3: until the mid 90’s, we did not have systematic methods
to cancel the IR divergences
2: until 2007-8, we did not have systematic methods
to compute the one-loop amplitudes
# NLO cross sections (2010)

2005 Les Houches list almost completed

<table>
<thead>
<tr>
<th>process wanted at NLO</th>
<th>background to</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. $pp \rightarrow VV + \text{jet}$</td>
<td>$t\bar{t}H$, new physics</td>
</tr>
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<td></td>
<td>$t\bar{t}H$, new physics</td>
</tr>
<tr>
<td></td>
<td>Dittmaier, Kallweit, Uwer; Campbell, Ellis, Zanderighi</td>
</tr>
<tr>
<td>2. $pp \rightarrow H + 2 \text{jets}$</td>
<td>$H$ in VBF</td>
</tr>
<tr>
<td></td>
<td>Campbell, Ellis, Zanderighi; Ciccolini, Denner Dittmaier</td>
</tr>
<tr>
<td>3. $pp \rightarrow t\bar{t}b\bar{b}$</td>
<td>$t\bar{t}H$</td>
</tr>
<tr>
<td></td>
<td>Bredenstein, Denner Dittmaier, Pozzorini; Bevilacqua, Czakon, Papadopoulos, Pittau, Worek</td>
</tr>
<tr>
<td>4. $pp \rightarrow t\bar{t} + 2 \text{jets}$</td>
<td>$t\bar{t}H$</td>
</tr>
<tr>
<td></td>
<td>Bevilacqua, Czakon, Papadopoulos, Worek</td>
</tr>
<tr>
<td>5. $pp \rightarrow VVb\bar{b}$</td>
<td>VBF $\rightarrow H \rightarrow VV$, $t\bar{t}H$, new physics</td>
</tr>
<tr>
<td></td>
<td>VBF: Bozzi, Jäger, Oleari, Zeppenfeld</td>
</tr>
<tr>
<td>6. $pp \rightarrow VV + 2 \text{jets}$</td>
<td>new physics</td>
</tr>
<tr>
<td></td>
<td>Berger, Bern, Dixon, Febres Cordero, Forde, Gleisberg, Ita, Kosower, Maitre; Ellis, Melnikov, Zanderighi</td>
</tr>
<tr>
<td>7. $pp \rightarrow V + 3 \text{jets}$</td>
<td>SUSY trilepton</td>
</tr>
<tr>
<td></td>
<td>Lazopoulos, Melnikov, Petriello; Hankele, Zeppenfeld; Binoth, Ossola, Papadopoulos, Pittau</td>
</tr>
<tr>
<td>8. $pp \rightarrow VVV$</td>
<td>Higgs, new physics</td>
</tr>
<tr>
<td>9. $pp \rightarrow b\bar{b}b\bar{b}$</td>
<td>C. Berger et al (BlackHat) 2010</td>
</tr>
</tbody>
</table>

$pp \rightarrow V + 4 \text{jets}$ new physics
in the past, long time span to add one more jet to a cross-section
in the last few years, huge progress

2 → 2 and 2 → 3 processes:
almost all computed and included into NLO packages

2 → 4 processes: a few computed

\[ \text{pp} \rightarrow t\bar{t}b\bar{b} \]
Bredenstein Denner Dittmaier Pozzorini; Bevilacqua Czakon Papadopoulos Pittau Worek 2009

\[ \text{pp} \rightarrow Q\bar{Q} + 2 \text{ jets} \]
Bevilacqua Czakon Papadopoulos Worek 2010

\[ \text{pp} \rightarrow H + 3 \text{ jets (VBF)} \]
Figy Hankele Zeppenfeld 2007

\[ \text{pp} \rightarrow V + 3 \text{ jets} \]
Berger et al. (BlackHat); K. Ellis Melnikov Zanderighi 2009

2 → 5 processes: just one

\[ \text{pp} \rightarrow V + 4 \text{ jets} \]
Berger et al. (BlackHat) 2010
$pp \rightarrow t \bar{t} + 2 \text{ jets}$ at NLO

Scale dependence of total x-sect

$\mu_R = \mu_F = \xi \mu_0$ with $\mu_0 = m_t$

dots: LO
solid: NLO
dash: NLO with jet veto of 50 GeV

reducible background to $pp \rightarrow H t \bar{t}$

NLO/LO $\equiv K$ factor $= 0.89$

Reduced theoretical error: 40-70% at LO; 12-13% at NLO
A C++ code based on generalised unitarity, and on-shell recursion for the rational parts computes
- real $W + 7$ parton amplitudes
- one-loop $W + 6$ parton amplitudes (leading colour)
Conclusions

an exciting period of **LHC** phenomenology is about to begin

signals and backgrounds for **Higgs** and **New Physics**

are evaluated with better and better accuracy, thanks to

a lot of progress in **pQCD** in the last few years in

- Monte Carlo generators
- **NLO** computations with many jets
**NLO assembly kit**

**example** \( e^+ e^- \rightarrow 3 \text{ jets} \)

**leading order** \[ |\mathcal{M}_{n}^{\text{tree}}|^2 \]

**NLO real**

\[ |\mathcal{M}_{n+1}^{\text{tree}}|^2 \quad \rightarrow \quad |\mathcal{M}_{n}^{\text{tree}}|^2 \times \int dPS |P_{\text{split}}|^2 \]

\[ = - \left( \frac{A}{\epsilon^2} + \frac{B}{\epsilon} \right) \]

**NLO virtual**

\[ d = 4 - 2\epsilon \]

\[ \int d^d l \ 2 (\mathcal{M}_{n}^{\text{loop}})^* \mathcal{M}_{n}^{\text{tree}} = \left( \frac{A}{\epsilon^2} + \frac{B}{\epsilon} \right) |\mathcal{M}_{n}^{\text{tree}}|^2 + \text{fin.} \]
NLO production rates

Process-independent procedure devised in the 90’s

- slicing
- subtraction
- dipole
- antenna

Giele Glover Kosower 1992-3
Frixion Kunszt Signer 1995; Nagy Trocsanyi 1996
Catani Seymour 1996
Kosower 1997; Campbell Cullen Glover 1998

\[
\sigma = \sigma^{\text{LO}} + \sigma^{\text{NLO}} = \int d\sigma^B_m J_m + \sigma^{\text{NLO}}
\]

\[
\sigma^{\text{NLO}} = \int_{m+1} d\sigma^R_{m+1} J_{m+1} + \int_m d\sigma^V_m J_m
\]

the 2 terms on the rhs are divergent in \(d=4\)

use universal IR structure to subtract divergences

\[
\sigma^{\text{NLO}} = \int_{m+1} \left[ d\sigma^R_{m+1} J_{m+1} - d\sigma^{R,A}_{m+1} J_m \right] + \int_{m} \left[ d\sigma^V_m + \int_1 d\sigma^{R,A}_{m+1} \right] J_m
\]

the 2 terms on the rhs are finite in \(d=4\)
Observables must be IR safe

observable function $J_m$

$J_m$ vanishes when one parton becomes soft or collinear to another one

$$J_m(p_1, \ldots, p_m) \to 0, \quad \text{if} \quad p_i \cdot p_j \to 0$$

$d\sigma^B_m$ is integrable over 1-parton IR phase space

$J_{m+1}$ vanishes when two partons become simultaneously soft and/or collinear

$$J_{m+1}(p_1, \ldots, p_{m+1}) \to 0, \quad \text{if} \quad p_i \cdot p_j \text{ and } p_k \cdot p_l \to 0 \quad (i \neq k)$$

$R$ and $V$ are integrable over 2-parton IR phase space

observables are IR safe

$$J_{n+1}(p_1, \ldots, p_j = \lambda q, \ldots, p_{n+1}) \to J_n(p_1, \ldots, p_{n+1}) \quad \text{if} \quad \lambda \to 0$$

$$J_{n+1}(p_1, \ldots, p_i, \ldots, p_j, \ldots, p_{n+1}) \to J_n(p_1, \ldots, p, \ldots, p_{n+1}) \quad \text{if} \quad p_i \to zp, \ p_j \to (1-z)p$$

for all $n \geq m$