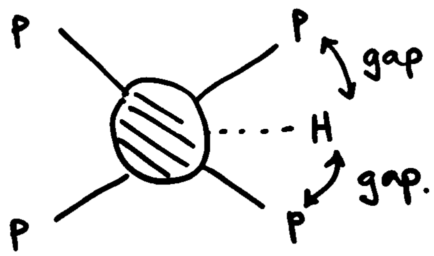
Review of diffractive Higgs production

Jeff Forshaw.



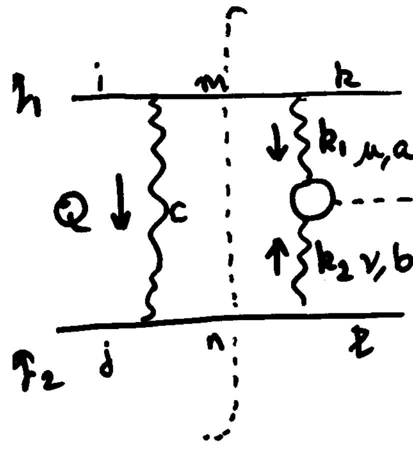
Two main approaches:

- "Durham" (perturbative QCD) .... Kaidalov, Khoze, Martin, Ryskin, Stirling ; ExHume.
  1997
- "Bialas – Landshoff" {non-perturbative QCD model}
  1991
  recently utilized by Boonekamp, Peschanski, Royon, Kúcs ; Bzdak ; DPEMC.

[won't discuss Petrov & Ryutin]

[won't discuss less exclusive final states]

$qq \to q + H + q$

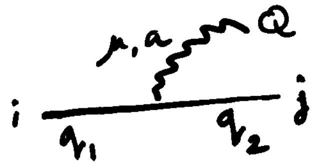


$q_1' = q_1 - Q - k_1$

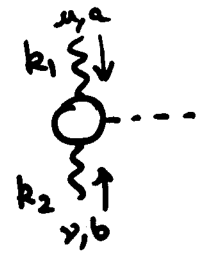
$q_2' = q_2 + Q - k_2$

$s = 2 q_1 \cdot q_2$

- Compute imaginary part
- Use eikonal approximation



$$\approx 2g\, q_1^\mu\, \tau^a_{ij}\, \delta_{\lambda\lambda'}$$

- 

$$\equiv V^{ab}_{\mu\nu} = \delta^{ab}\left(g_{\mu\nu} - \frac{k_{2\mu} k_{1\nu}}{k_1 \cdot k_2}\right) V$$

(+ NLO K-factor)

$$V \equiv \frac{M_H^2 \alpha_s}{4\pi v} F_s\left(\frac{M_H^2}{4 m_t^2}\right)$$

$$\hookrightarrow \operatorname{Im} A^{ik}_{j\ell} = \frac{1}{2} \int d(PS)_2\, \delta((q_1 - Q)^2)\, \delta((q_2 + Q)^2)$$

$$\times 2 \times \frac{2g q_1^\alpha\, 2g q_{2\alpha}}{Q^2} \times \frac{2g q_1^\mu}{k_1^2}\, \frac{2g q_2^\nu}{k_2^2}$$

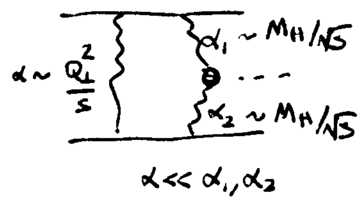
$$\times V^{ab}_{\mu\nu}\, \tau^c_{im}\, \tau^c_{jn}\, \tau^a_{mk}\, \tau^b_{n\ell}$$

$$Q = \alpha q_1 + \beta q_2 + Q_\perp$$

$$(q_1 - Q)^2 = 0 \Rightarrow \beta = Q_\perp^2/s$$

$$(q_2 + Q)^2 = 0 \Rightarrow \alpha = -Q_\perp^2/s$$

$$\Big\} \; Q_\perp^2 \simeq Q^2 = -\underline{Q}_T^2$$



$$\int d(PS)_2 \rightarrow \int \frac{d^4Q}{(2\pi)^2} = \frac{s}{2}\frac{1}{(2\pi)^2}\int d\alpha\, d\beta\, d^2\underline{Q}_\perp$$

$$\mathrm{Im}\, A^{ik}_{jl} = \int \frac{d^2 \underline{Q}_\perp}{(2\pi)^2}\, \frac{2s}{\underline{Q}_\perp^2}\, \frac{1}{\underline{k}_1^2}\, \frac{1}{\underline{k}_2^2}\, \frac{g^4}{2s}\left[q_1^\mu V^{ab}_{\mu\nu} q_2^\nu\right]$$

$$\times \underbrace{\tau^a_{mk}\, \tau^b_{nl}\, \tau^c_{im}\, \tau^c_{jn}}_{\frac{\delta^{ab}}{4N_c^2} \text{ after averaging over colours}}$$

$$q_1^\mu V^{ab}_{\mu\nu} q_2^\nu = V \delta^{ab}\left\{\frac{-\underline{k}_{1\perp}\cdot \underline{k}_{2\perp}}{M_H^2}\, s\right\} \qquad \left[\begin{array}{l} k_i \simeq \alpha_i P_i + k_{i\perp} \\ \alpha_1 \alpha_2 s \simeq M_H^2 \end{array}\right]$$

"spin selection rule"

$$k_1^\mu V_{\mu\nu} = k_2^\nu V_{\mu\nu} = 0 \quad \text{(gauge invariance)}$$

ie, $$\frac{k_{1\perp}^\mu}{\alpha_1} V_{\mu\nu} = -q_1^\mu V_{\mu\nu} \quad \text{and} \quad \frac{k_{2\perp}^\nu}{\alpha_2} V_{\mu\nu} = -q_2^\nu V_{\mu\nu}$$

$$\therefore\; q_1^\mu V_{\mu\nu} q_2^\nu = \frac{s}{M_H^2}\, k_{1\perp}^\mu k_{2\perp}^\nu V_{\mu\nu}$$ ⟵ as if incoming gluons are polarized as $\varepsilon_i \propto k_{i\perp}$

$$\left[\text{if } q'_{1\perp} = 0 \;,\; q'_{2\perp} = 0 \quad \text{then} \quad k_{1\perp} = -k_{2\perp} = -Q_\perp\right]$$

$\hookrightarrow \varepsilon_{1\perp} = -\varepsilon_{2\perp}$

$$= \frac{-s}{M_H^2}\, \underline{k}_{1\perp}\cdot \underline{k}_{2\perp} \approx \frac{s}{M_H^2}\, \underline{Q}_\perp^2$$

$$\frac{\mathrm{Im}\,A}{s} = \frac{N_c^2-1}{N_c^2} \times 4\alpha_s^2 \int \frac{d^2\underline{Q}_\perp}{\underline{Q}_\perp^2\,\underline{k}_1^2\,\underline{k}_2^2}\,\frac{(-\underline{k}_{1\perp}\cdot\underline{k}_{2\perp})}{M_H^2} \underbrace{\left[\frac{M_H^2\,\alpha_s}{4\pi}\left(\sqrt{2}\,G_F\right)^{\frac{1}{2}}\frac{2}{3}\right]}_{V\ (m_t\to\infty)}$$

$$d\sigma\,(qq\to qHq) = \frac{1}{2s}\,\frac{d^3q_1'}{(2\pi)^3}\,\frac{d^3q_2'}{(2\pi)^3}\,\frac{1}{2E_1'\,2E_2'}\,|A|^2$$

$$\times\,\frac{d^3q_H}{(2\pi)^3}\,\frac{1}{2E_H}\,(2\pi)^4\,\delta^{(4)}(q_1+q_2-q_1'-q_2'-q_H)$$

$$d^3\underline{q}_1'\,d^3\underline{q}_2'\,d^3\underline{q}_H\,\delta^{(4)}(\ldots) = d^2\underline{q}_1'\,d^2\underline{q}_2'\,dy_H\,E_H$$

$$\Rightarrow\quad \frac{d\sigma}{d^2\underline{q}_1'\,d^2\underline{q}_2'\,dy_H} = \left(\frac{N_c^2-1}{N_c^2}\right)^2 \frac{\alpha_s^6}{(2\pi)^5}\,\frac{G_F}{\sqrt{2}}\left[\int \frac{d^2\underline{Q}_\perp}{2\pi}\,\frac{\underline{k}_{1\perp}\cdot\underline{k}_{2\perp}}{\underline{Q}_\perp^2\,\underline{k}_{1\perp}^2\,\underline{k}_{2\perp}^2}\,\frac{2}{3}\right]^2$$

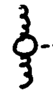
$$\left[\text{if } q_{1\perp}'\simeq 0\,,\ q_{2\perp}'\simeq 0 \qquad \simeq \frac{1}{\underline{Q}_\perp^4}\right]$$

{ key intermediate result for both Durham & BL approaches }

(BL missed a factor 2) $\sqrt{2}$ in Higgs width $\Gamma(H\to gg)$)

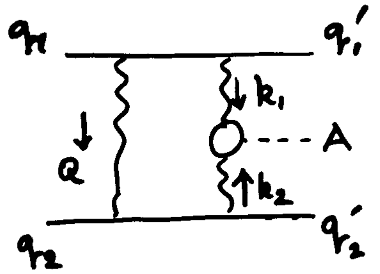
Now need to progress from $qq\to qHq$ to $pp\to pHp$ .... point of departure

PSEUDOSCALAR HIGGS

 $\ldots \propto \varepsilon^{\mu\nu\rho\sigma} k_{1\rho} k_{2\sigma}$

- As for 0^+ case except

$$\underline{k}_1 \cdot \underline{k}_2 \longrightarrow (\underline{k}_1 \times \underline{k}_2) \cdot \underline{n}$$ ← unit vector along beam axis



if $\underline{q}_1 = \underline{q}_2 = 0$

then $\underline{q}_1' = -\underline{Q} - \underline{k}_1$

$\underline{q}_2' = +\underline{Q} - \underline{k}_2$

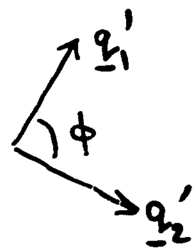
Have $$\int \frac{d^2 \underline{Q}}{\underline{Q}^2} \frac{1}{\underline{k}_1^2} \frac{1}{\underline{k}_2^2} \left\{ (\underline{q}_1' + \underline{Q}) \times (\underline{q}_2' - \underline{Q}) \right\} \cdot \underline{n}$$

$$\Rightarrow \int \frac{dQ_T^2}{Q_T^2} \frac{1}{Q_T^4} (\underline{q}_1' \times \underline{q}_2') \cdot \underline{n}$$ ← in limit $|\underline{q}_1'|, |\underline{q}_2'| \ll |\underline{Q}_T|$

Suppressed by $\sim \frac{|t|}{\langle Q_T^2 \rangle}$ relative to 0^+

more **IR sensitive**

outgoing protons like to be at **right angles** in azimuth $\sim \sin^2 \phi$

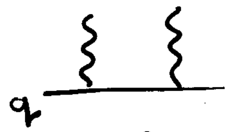


ie can enhance 0^- rate* by cutting on $|\underline{q}_1'|, |\underline{q}_2'| > q_{cut}$

(*Relative to 0^+ rate)

Aside if CP violated in Higgs sector then can form a CP asymmetry $$\frac{\sigma(\phi < \pi) - \sigma(\phi > \pi)}{\sigma(\phi < \pi) + \sigma(\phi > \pi)}$$ can be formed.

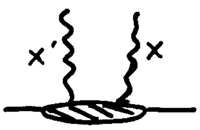
Durham approach

 $\longrightarrow$ 

$$\frac{\alpha_s C_F}{\pi} \longrightarrow \frac{\partial G(x, Q_t^2)}{\partial \ln Q_t^2}$$

$$\left[\begin{array}{l} \text{DGLAP}: \quad (q(x) = \delta(1-x)) \\ \dfrac{\partial G}{\partial \ln Q^2} \simeq C_F \dfrac{\alpha_s}{\pi} \\ \qquad\qquad \uparrow \\ \qquad\qquad P_{gq}(z)\big|_{z\to 0} \end{array} \right]$$

Complications I :



$$x' = \frac{Q_\perp^2}{s} \ll x \sim \frac{M_H}{\sqrt{s}} \ll 1$$

Really need "off-diagonal" partons

$$\frac{\partial G}{\partial \ln Q^2} \longrightarrow \frac{\partial G(x, Q_t^2)}{\partial \ln Q_t^2} \left[\frac{2^{2\lambda+3}}{\sqrt{\pi}} \frac{\Gamma(\lambda + 5/2)}{\Gamma(\lambda+4)} \right]$$

$\Big\{$ Shuvaev et al.
Assumes $x' \ll x$
and $G \sim x^{-\lambda}$

$\Downarrow$

Enhancement by a factor $\simeq (1.2)^4 \simeq 2$ in Xsecn at LHC energies. ($\lambda \simeq 0.2$)

Complications II :

Sudakov (next slide)

Need to modify t-dependence

$$t_i = (q_i' - q_i)^2 \approx -(\underline{q}_{i\perp}' - \underline{q}_{i\perp})^2 = (\underline{q}_{i\perp}')^2$$

$$d\sigma \longrightarrow d\sigma\, e^{bt_1} \times e^{bt_2}$$

$\Rightarrow$ Choice of b ?

$$\left[\sim \int dt_1\, dt_2\, e^{b(t_1+t_2)} \sim \frac{1}{b^2} \right]$$

Thus, modulo Sudakov logs, we have

$$\frac{d\sigma}{dy_H} \simeq \frac{1}{256\pi \underline{\underline{b}}^2} \frac{\alpha_s^2 G_F \sqrt{2}}{9} \left[\int \frac{d^2 Q_\perp}{Q_\perp^4} f\underline{\underline{(x_1, Q_\perp^2)}} f\underline{\underline{(x_2, Q_\perp^2)}} \right]^2$$

$$f(x_1, Q_\perp^2) = \frac{\partial G(x_1, Q_\perp^2)}{\partial Q_\perp^2} \quad (x_i = \alpha_i)$$

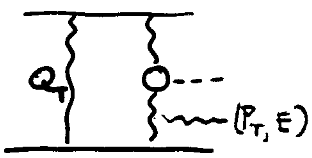
SUDAKOV

- So far all cross-sections are **DIVERGENT**

$$\int_0 \frac{dQ_T^2}{Q_T^4} \qquad \left(\text{and} \quad \int_0 \frac{dQ_T^2}{Q_T^6}\right)$$

{ not quite so bad due to anomalous dimension of gluon density $\sim (Q_T^2)^\gamma$ }

But these exist Sudakov logarithms



$P_T < Q_T$: soft gluon screens emission

Emission probability $\approx C_A \displaystyle\int_{Q_T^2}^{M_H^2/4} \frac{dP_T^2}{P_T^2} \frac{\alpha_s(P_T^2)}{\pi} \int_{P_T}^{\frac{1}{2}M_H} \frac{dE}{E}$

(soft & collinear approximation i.e. double log approx.)

$$\left(\sim \frac{\alpha_s C_A}{\pi} \, \frac{1}{4} \ln^2 \frac{M_H^2}{4Q_T^2}\right)$$

exponentiating generates a factor in amplitude of

$$\exp(-S) = \exp\left(-\frac{C_A}{\pi} \int_{Q_T^2}^{\frac{1}{4}M_H^2} \alpha_s \frac{dP_T^2}{P_T^2} \int_{P_T}^{M_H/2} \frac{dE}{E}\right) \longleftarrow \text{double logs}$$

$$= \exp\left(-\int_{Q_T^2}^{M_H^2/4} \frac{\alpha_s(P_T^2)}{2\pi} \frac{dP_T^2}{P_T^2} \int_0^{1-\Delta} \left\{ z P_{gg}(z) + \sum_q P_{qg}(z) \right\} dz \right)$$

double and single logs

Collinear **AND** soft logs if

$$\Delta = \frac{P_T}{(P_T + 0.62 M_H)}$$

$\boxed{\text{As } Q_T \to 0 \text{ so the screening gluon fails to screen and } P_T \approx 0 \text{ emission is allowed. Hence } e^{-S} \text{ vanishes faster than any power of } Q_T.}$

☞ Sudakov factor ensures all cross-sections are formally convergent

<u>But</u> Typical Q_T is still small.

Saddle point in $\displaystyle\int \frac{dQ^2}{Q^n}\, e^{-S(Q^2, M_H^2)} f(x_1, Q^2)\, f(x_2, Q^2)$

occurs at $\displaystyle \log \frac{M_H^2}{4Q^2} = \frac{2\pi}{N_c \alpha_s(Q^2)} \left(\frac{n}{2} - 1 - 2\gamma \right)$

assuming $f \sim (Q^2)^\gamma$

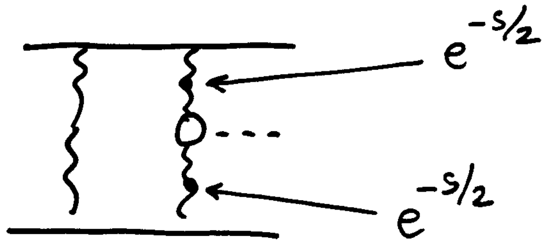
So $\displaystyle Q \sim \frac{M_H}{2} \exp\left(- \frac{2\pi}{N_c \alpha_s} \frac{\left[\frac{n}{2} - 1 - 2\gamma \right]}{2} \right)$

$\alpha_s = 0.2$, $M_H = 100$ GeV, $n = 4$, $\gamma = 0.2$ $\Rightarrow$ 2 GeV

(" " $n = 6$ " $\Rightarrow$ $\ll 1$ GeV)

☞ $Q \simeq 2$ GeV for 0^+ is just in domain of pQCD.

$$\boxed{\text{It is crucial to sum the single logarithms since double log approx. overestimates Sudakov suppression by a factor} \sim 3}$$



$f(x, Q_t^2)$ = distribution of gluons at Q_t

$= \frac{\partial}{\partial \ln Q_t^2} G(x, Q_t^2)$ distribution of gluons up to Q_t without Sudakov

Should use

$$f(x, Q_t^2) = \frac{\partial}{\partial \ln Q_t^2} \Big\{ \underbrace{e^{-S/2}\, G(x, Q_t^2)} \Big\}$$

distribution of gluons up to Q_t and no emission up to M_A.

At double log level $f(x_1, Q_t^2)\, f(x_2, Q_t)^2 = e^{-S} \frac{\partial G(x_1, Q_t^2)}{\partial \ln Q_t^2} \frac{\partial G(x_2, Q_t^2)}{\partial \ln Q_t^2}$

$\frac{\partial e^{-S/2}}{\partial \ln Q_t^2}$ Correction is very important
~ 10 enhancement

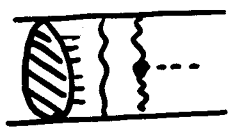
{ formally : problems as $Q_t \to 0$
IR cutoff }

GAP SURVIVAL

- Want to compute

  $P(pHp \mid gaps)$

  Apart from Sudakov there are other ways to fill in gaps "soft rescattering", "multiparton interactions"



- Assume that $P(pHp \mid gaps) = P(pHp) \times \underbrace{P(\text{gap not filled})}_{= S^2}$

  "gap survival factor"

- Simplest ansatz is that rescattering ~~to~~ ~~a~~ ~~single~~ can be described by Poisson statistics

  let $\Omega(b)$ be the mean number of rescattering events for a pp collision at impact parameter b

  then $P_n = \frac{\Omega(b)^n}{n!} \exp(-\Omega(b))$ is the probability of having n rescatterings. $P_0 = \exp(-\Omega(b))$

  Hence
$$S^2 \simeq \frac{\int d^2\underline{b}\; e^{-\Omega(b)} \, |M_{p+H+p}(b)|^2}{\int d^2\underline{b}\; |M_{p+H+p}(b)|^2}$$

- In such a "single channel" approach

$$\sigma_{\text{inelastic}} = \int d^2\underline{b}\,\left(1 - e^{-\Omega(b)}\right)$$

$$\left\{\begin{array}{l} \text{Hence } \sigma_{\text{elastic}} = \int d^2\underline{b}\,\left(1 - e^{-\Omega/2}\right)^2 \\ \text{and } \sigma_{\text{tot}} = 2\int d^2 b\,\left(1 - e^{-\Omega/2}\right) \end{array}\right\}$$

such that $\sigma_{\text{tot}} = \sigma_{\text{elastic}} + \sigma_{\text{inelastic}}$

$\Rightarrow$ $\Omega \ll 1$

$$\sigma_{\text{tot}} \simeq \int d^2 b\ \Omega(b) \longleftarrow$$ identify with single $\mathbb{P}$ exchange

eg $$\Omega(b) = \underbrace{\sigma_0 \left(\frac{s}{s_0}\right)^{\Delta}}_{=\sigma_{\text{tot}}} \times \frac{1}{2\pi B} \exp\left(-b^2/2B\right)$$

fit σ_0, Δ & $B(s)$ to σ_{tot} and σ_{elastic} data. (Block & Halzen)

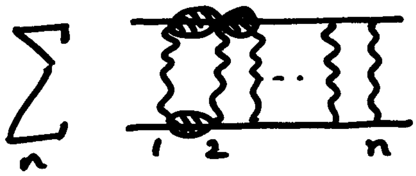
- To compute S^2 need b dependence of $|M_{p+H+p}|^2$

if $$|M_{p+H+p}|^2 \sim \left| \int e^{-b_0^2 q_t^2/2}\, e^{i\underline{q}\cdot\underline{b}}\, d^2\underline{q}_t \right|^2$$

$b_0 \simeq 5.5\,\text{GeV}^{-2}$ (± ?)

$$\sim e^{-b^2/2b_0^2}$$

- KKMR use a two channel eikonal model.

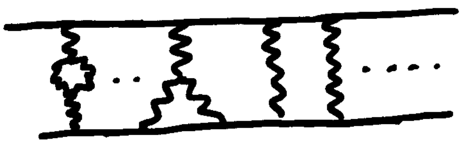


takes account of diffraction

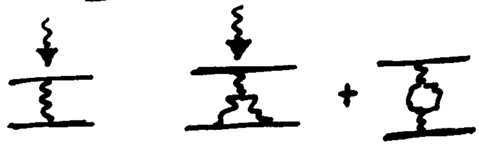
Assume

$(\gamma \simeq 0.4)$

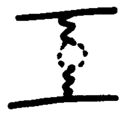
Also include high mass diffraction via triple regge



ie $\Omega = \Omega_{P} + \Omega_{D}$



And use a modified $\alpha_{P}(t)$ to account for π loops at low t ie, $\alpha_{P} = \alpha(0) + \alpha'(t) - \Delta\left(m_\pi^2/t\right)$



$$\boxed{\text{Most (all?) eikonal models yield similar predictions for } S^2 \text{ provided they are tuned to } \sigma_{tot} \text{ \& } \sigma_{elastic}}$$

eg/ for central diffraction at LHC $S^2 \simeq 2\text{-}3\%$

Bialas – Landshoff approach

$$\frac{d\sigma}{d^2\underline{q}_1'\, d^2\underline{q}_2'\, dy_H} = \left(\frac{N_c^2-1}{N_c^2}\right)^2 \frac{\alpha_s^6}{(2\pi)^5} \frac{G_F}{\sqrt{2}} \left[\int \frac{d^2\underline{Q}_\perp}{2\pi} \frac{\underline{k}_{1\perp}\cdot \underline{k}_{2\perp}}{\underline{Q}_\perp^2\, \underline{k}_{1\perp}^2\, \underline{k}_{2\perp}^2} \frac{2}{3} \right]^2$$

$$\frac{g^2}{k^2} \to A\, e^{-k^2/\mu^2}$$

$\left\{ \begin{array}{l} \mu \simeq 1 \text{ GeV assumed} \\ A \text{ fixed by } \sigma_{tot} \\ g^2 = 4\pi \text{ assumed.} \end{array} \right\}$

"additional ... interactions .... will generate extra particles .... Thus our calculation really is an inclusive one." Bialas-Landshoff

$\Vert$

{ No Sudakov or gap survival }

Means $\dfrac{\operatorname{Im} A}{s} \approx C = 1 \times 10^{-3}\ \text{GeV}^{-3}$

[should be $\times\sqrt{2}$ (error in B&L)]

$A(pp \to pHp) = g \times A(qq \to qHq)$

Reggeization :

$$A \to A \left(\frac{1}{x_1}\right)^{\alpha(t_1)-1} \left(\frac{1}{x_2}\right)^{\alpha(t_2)-1} F(t_1)\, F(t_2)$$

$\alpha(t) = 1.08 + [0.25\,\text{GeV}^{-2}]\, t$

$\left\{ \begin{array}{l} F(t) = e^{\lambda t} \\ \lambda = 2\ \text{GeV}^{-2} \end{array} \right\}$

This is the approach implemented in DPEMC

(Boonekamp, Kúcs, Peschanski, Royon)