Drell-Yan process and heavy boson production at hadron colliders

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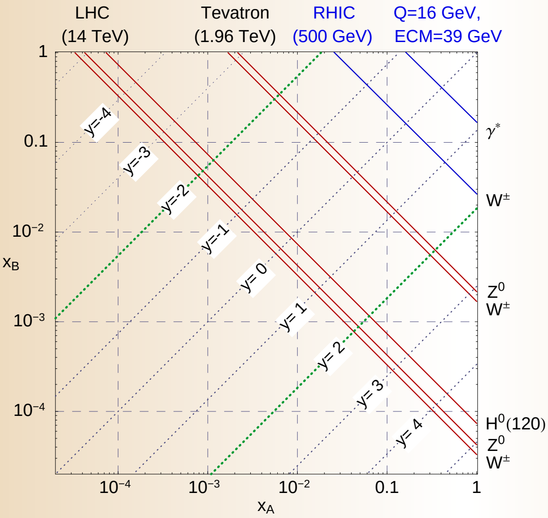
Some references

- My slides are available from the CTEQ webpage or *http://hep.pa.msu.edu/nadolsky/tmp/cteqX.pdf*
- Feynman rules for tree helicity amplitudes involving massive quarks and bosons
  Schwinn, Weinzierl, hep-th/0503015
- Gluon PDF in a pion (depends on theory assumptions)
  Sutton, Martin, Roberts, Stirling, PRD 45, 2349 (1992); Gluck, Reya, Stratmann, hep-ph/9711369
- Multiple parton interactions in Pythia
  Sjostrand, Mrenna, Skands, hep-ph/0603175, chapters 11.2-11.4

Outline

- Saturday
  - low-Q lepton pair production
  - heavy electroweak bosons
  - kinematics
  - leading-order (LO) cross sections
  - NLO/NNLO results
- Monday
  - modern applications
  - QCD factorization and resummation of large logarithms
  - new physics searches

Typical parton momentum fractions



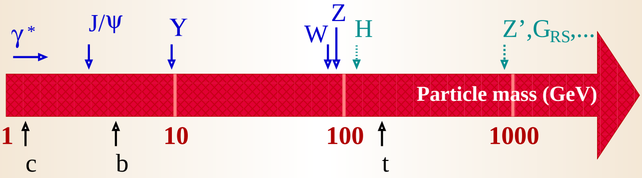
$$x_{A,B} \equiv \frac{Q}{\sqrt{s}} e^{\pm y}$$

Born level: $p_a^\mu = x_A p_A^\mu$, $p_b^\mu = x_B p_B^\mu$

Typical rapidities in the experiment: $|y| \lesssim 2$

- experiments at higher energies are sensitive to PDF's at smaller x

Particle states probed by Drell-Yan-like processes



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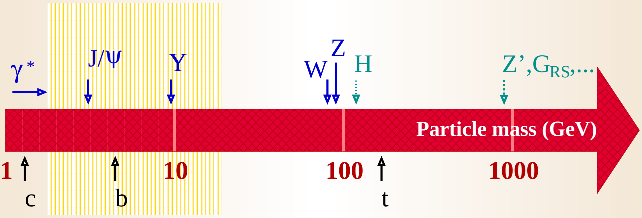
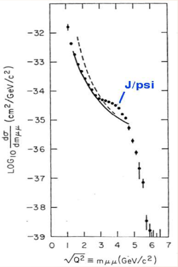


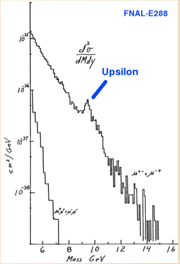
$pN \xrightarrow{\gamma^*} \ell^+\ell^- X$ at $Q < 20$ GeV

- Continuous γ^* cross section
- Multiple quarkonium resonances (neglected in the PDF fit)

▲ J/ψ ($c\bar{c}$)– found in e^+e^- scattering (1974)

▲ Υ ($b\bar{b}$)– found in $pN \to \mu^+\mu^- X$ (FNAL-E288, 1977)





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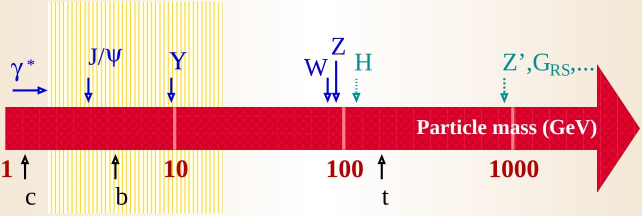
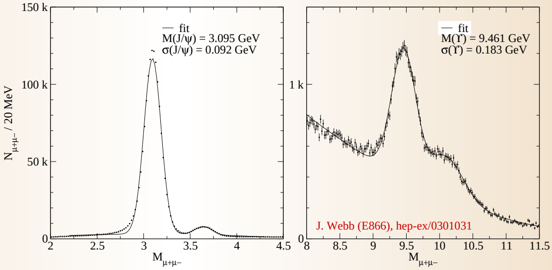


J/ψ, Υ resonances shown with better resolution (FNAL-E866)



Constraints on quark sea from $pN \to \ell^+\ell^- X$

($N = p, d, Fe, Cu, ..$)

$$\frac{d\sigma_{pp}}{dQ^2dy} \sim \left(\frac{2}{3}\right)^2 \left[u_A\bar{u}_B + \bar{u}_A u_B\right] + \left(-\frac{1}{3}\right)^2 \left[d_A\bar{d}_B + \bar{d}_A d_B\right] + \text{ smaller terms}$$

$\Rightarrow$ sensitivity to $\bar{q}(x, Q)$

Assuming charge symmetry between protons and neutrons ($u_p = d_n,\, u_n = d_p$):

$$\frac{d\sigma_{pn}}{dQ^2dy} \sim \left(\frac{2}{3}\right)^2 \left[u_A\bar{d}_B + \bar{u}_A d_B\right] + \left(-\frac{1}{3}\right)^2 \left[d_A\bar{u}_B + \bar{d}_A u_B\right] + \text{ smaller terms}$$

If deuterium binding corrections are neglected:

$q_d(x) \approx q_p(x) + q_n(x)$

At $x_A \gg x_B$ (large y): $\bar{q}(x_A) \sim 0$ and $4u(x_A) \gg d(x_A)$

$$\frac{\sigma_{pd}}{2\sigma_{pp}} \approx \frac{1}{2}\frac{\left(1+\frac{d_A}{4u_A}\right)[1+r]}{\left(1+\frac{d_A}{4u_A}r\right)} \approx \frac{1}{2}(1+r), \text{ where } r \equiv \bar{d}(x_B)/\bar{u}(x_B)$$

$\therefore\ \sigma_{pd}/(2\sigma_{pp})$ constrains $\bar{d}(x,Q)/\bar{u}(x,Q)$ at moderate x

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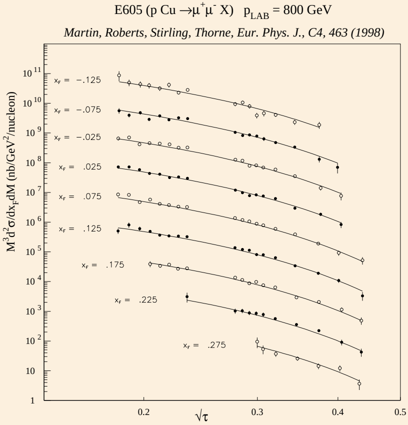
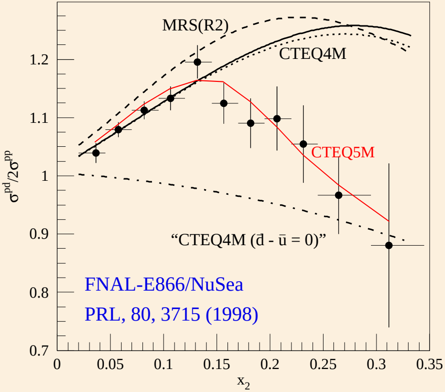
$\therefore \sigma_{pd}/(2\sigma_{pp})$ constrains $\bar{d}(x, Q)/\bar{u}(x, Q)$ at moderate x

Theory vs. experiment

Cross section at $Q = 4 - 17$ GeV



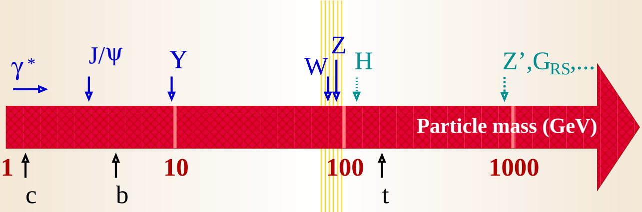
$\sigma_{pd}/(2\sigma_{pp})$ at large $x_F = x_A - x_B$



Theory curves reflect different assumptions about $\bar{d}/\bar{u}$

The recent PDF fits (e.g., CTEQ5M) quantitatively account for the violation of $SU(2)$ symmetry in the quark sea

Particle states probed by Drell-Yan-like processes



W and Z boson production

- good convergence of the α_s series
- small backgrounds
- separation of PDF flavors (via the CKM matrix)
- sensitivity to new physics

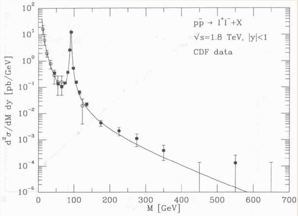


Fig. 9.5. The lepton pair cross section in $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV, with CDF data from ref. [12] (open circles) and ref. [13] (solid circles). The curve is the next-to-leading-order QCD prediction using the parton distributions from ref. [9]

Z pole and γ^* continuum in $\ell^+\ell^-$ production

Leptonic vs. hadronic decay modes

The W and Z branching ratios $\mathrm{Br}_i \equiv \Gamma_i/\Gamma$ are

- $\mathrm{Br}\,[W \to \ell\nu_\ell] \approx 3 \times 11\%$, $\mathrm{Br}\,[W \to \mathrm{jets}] \approx 68\%$
- $\mathrm{Br}\,[Z \to \ell^+\ell^-] = 3 \times 3.36\%$, $\mathrm{Br}\,[Z \to \nu_\ell\bar{\nu}_\ell] = 3 \times 6.67\%$, $\mathrm{Br}\,[Z \to \mathrm{jets}] \approx 70\%$

At $\sqrt{s}$ of a few TeV, hadronic W, Z decays cannot be observed because of the large background (mostly $qg, gg \to \mathrm{jets}$)

Despite small branching ratios, the only viable decay modes are

- $Z \to e^+e^-$, $Z \to \mu^+\mu^-$
- $W \to e + \nu_e$, $W \to \mu + \nu_\mu$, with neutrinos identified by missing transverse energy $\not{E}_T$

A quiz on W boson kinematics

Consider $AB \to (W^+ \to e^+\nu_e)X$ decay in the lab frame.
The most probable transverse momentum Q_T of the W boson is

a) $Q_T = \sqrt{s}/2$

b) $Q_T = |\vec{p}_T^{\,e}| + \not{E}_T$

c) $Q_T = 0$

d) $Q_T = 2 - 5$ GeV,
depending on $\sqrt{s}$

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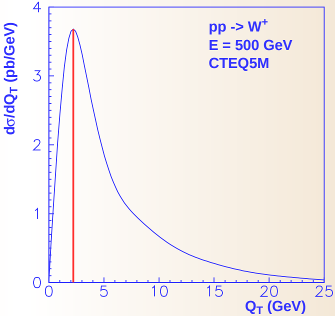


The LO condition $Q_T = 0$ (corresponding to no QCD radiation) is never realized because of self-suppression of very soft QCD contributions (Sudakov suppression). To predict $d\sigma/dQ_T$ at $Q_T \ll Q \sim M_W$, one needs to resum such soft contributions to all orders in α_S.

A quiz on W boson kinematics

Consider $AB \to (W^+ \to e^+\nu_e)X$ decay in the lab frame.
The most probable transverse momentum p_T^e of the positron is

a) $p_T^e = 0 - 5$ GeV

b) $p_T^e \approx 40$ GeV

c) $p_T^e \approx 80$ GeV

d) $p_T^e = Q_T/2$

A quiz on W boson kinematics

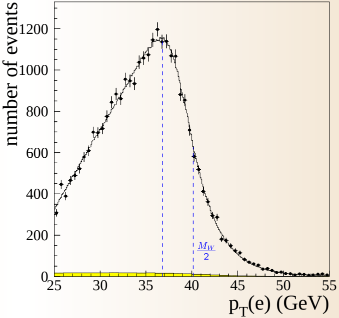
Consider $AB \to (W^+ \to e^+\nu_e)X$ decay in the lab frame.
The most probable transverse momentum p_T^e of the positron is

a) $p_T^e = 0 - 5$ GeV

b) $p_T^e \approx 40$ GeV $= M_W/2$

c) $p_T^e \approx 80$ GeV

d) $p_T^e = Q_T/2$



$d\sigma/dp_T^e$ has a kinematical (Jacobian) peak,

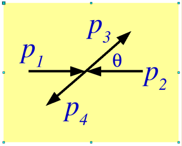
- ...located exactly at $p_T^e = M_W/2$ if $Q_T = 0$ and $Q = M_W$
- ...smeared by higher-order EW and soft QCD corrections

The origin of the Jacobian peak

In the Collins-Soper W rest frame, for $Q = M_W$:

$$p_T^e = |\vec{p}_1| \sin\theta_* = \frac{M_W}{2}\sin\theta_*$$

$$\frac{d\sigma}{d\cos\theta_*} = \sum_j F_j(Q, Q_T, y) a_j(\theta_*, \varphi_*)$$



$a_1 = 1 + \cos^2\theta_*$, $a_2 = 2\cos\theta_*$, etc. (smooth functions)

$$\frac{d\sigma}{dp_T^e} = \underbrace{\left|\frac{d\cos\theta_*}{dp_T^e}\right|}_{\text{Jacobian}} \frac{d\sigma}{d\cos\theta_*} = \frac{1}{\sqrt{1-\left(\frac{2p_T^e}{M_W}\right)^2}} \frac{4p_T^e}{M_W^2} \frac{d\sigma}{d\cos\theta_*}$$

$$\frac{d\sigma}{dp_T^e} \to \infty \text{ if } p_T^e \to M_W/2 \text{ (!)}$$

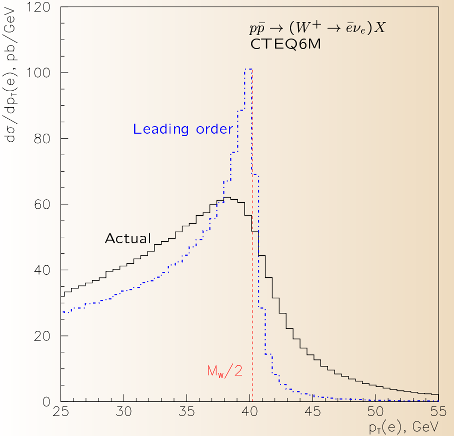
The origin of the Jacobian peak

$$\text{If } Q_T = 0\text{:} \quad (p_T^e)_{\text{lab frame}} = (p_T^e)_{\text{CS frame}}$$

(the boost from the CS frame to the lab frame is along the $z-$axis)

Corrections to $d\sigma/dp_T^e$ are of order

- $\mathcal{O}(\Gamma_W^2/M_W^2)$ due to the non-zero W width Γ_W ($Q \neq M_W$)
- $\mathcal{O}(Q_T/Q)$ due to the boost $\Rightarrow$ sensitivity to the shape of $d\sigma/dQ_T$ (soft radiation) at $Q_T \ll Q$



A similar Jacobian peak is present in $d\sigma/dp_T^\nu$

Lepton transverse mass

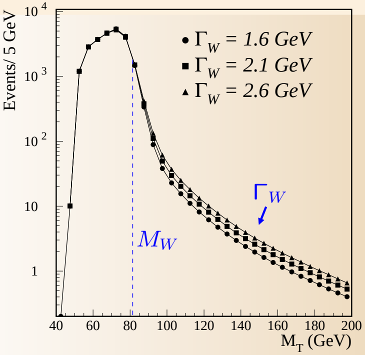
Definition

$M_T^{e\nu} \equiv 2(p_T^e p_T^\nu - \vec{p}_T^{\,e} \cdot \vec{p}_T^{\,\nu})$ in the lab frame *(Smith, van Neerven, Vermaseren, 1983)*

Exercise

Assuming $Q_T = 0$, verify that there is a Jacobian peak in $d\sigma/dM_T^{e\nu}$ at $M_T^{e\nu} = M_W$

- Corrections to $d\sigma/dM_T^{e\nu}$ are of order $\mathcal{O}(Q_T^2/Q^2) \Rightarrow$ reduced sensitivity to small-Q_T soft contributions
- $d\sigma/dM_T^{e\nu}$, $d\sigma/dp_T^e$, and $d\sigma/dp_T^\nu$ are important observables. They are commonly used to measure M_W. Γ_W is found from $d\sigma/dM_T^{e\nu}$ at large $M_T^{e\nu}$



W and Z production as a "luminosity monitor"

(Dittmar, Pauss, Zurcher; Khoze, Martin, Orava, Ryskin; Giele, Keller';...)

- Cross sections for $pp \to W^{\pm}X$, $pp \to Z^0X$ at the LHC can be measured with accuracy $\delta\sigma/\sigma \sim 1\%$ (tens of millions of events even at low luminosity)
- These measurements can be employed to
  - measure all other LHC cross sections in units of $\sigma_{W,Z}^{LHC}$
  - measure magnitudes of $\sigma_{W,Z}^{LHC}$; use them to monitor the LHC luminosity in real time
  - precisely measure PDF's (parton luminosities); reduce theory uncertainties for tiny new physics signals and huge SM backgrounds

The accuracy of luminosity monitoring in $p\bar{p}$ elastic scattering at the Tevatron is of order 5%

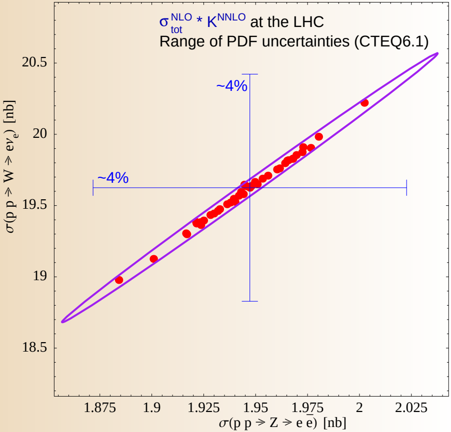
Theoretical aspects of luminosity monitoring

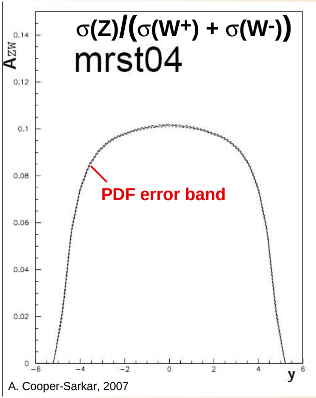
Several factors contribute to W & Z cross sections at a percent level, including

- $\mathcal{O}(\alpha_s^2)$, or NNLO, QCD corrections
- $\mathcal{O}(\alpha)$, or NLO, EW corrections
- PDF uncertainties
- Experimental acceptance
- QCD and EW showering (all-orders resummations)

Sometimes, these effects (e.g., PDF dependence or constant K-factors) may cancel in ratios, but in many cases they do not

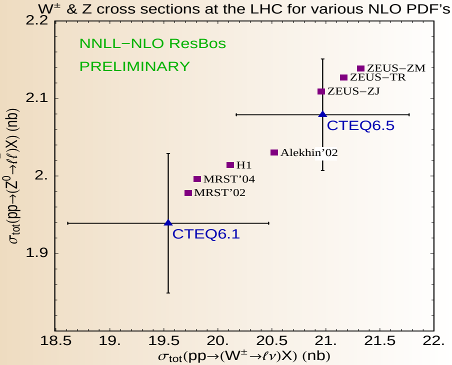
Ratios of W and Z cross sections





Radiative contributions, PDF dependence have similar structure in W, Z, and alike cross sections; cancel well in Xsection ratios

σ_Z vs. σ_W at NLO for various PDF sets



However, the PDF errors for cross sections themselves are still very appreciable

CTEQ6.5/CTEQ6.1∼1.07

- reflects a 7% increase in parton luminosities $\mathcal{L}_{q_i\bar{q}_j}(x_1,x_2,Q) = q_i(x_1,Q)\bar{q}_j(x_2,Q)$ in the relevant x and Q ranges for u, d, s quarks (consequence of improved treatment of heavy-flavor masses in DIS at HERA)

Charged lepton asymmetry at the Tevatron

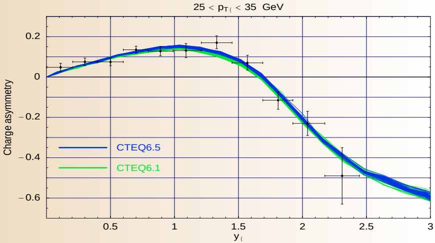
$$A_{ch}(y_e) \equiv \frac{\frac{d\sigma^{W^+}}{dy_e} - \frac{d\sigma^{W^-}}{dy_e}}{\frac{d\sigma^{W^+}}{dy_e} + \frac{d\sigma^{W^-}}{dy_e}}$$

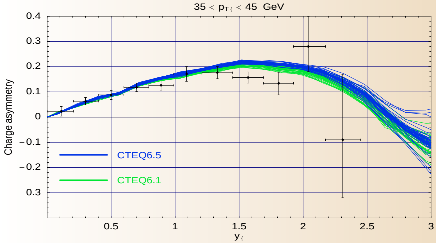
- related to the boson Born-level asymmetry when y_e is large

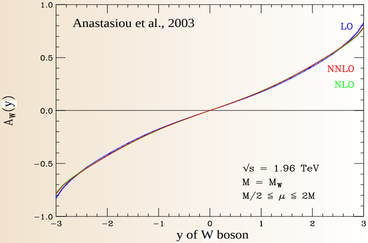
$$A_{ch}(y) \stackrel{y \to y_{max}}{\longrightarrow} \frac{r(x_B) - r(x_A)}{r(x_B) + r(x_A)}, \; r(x) \equiv \frac{d(x, M_W)}{u(x, M_W)}$$

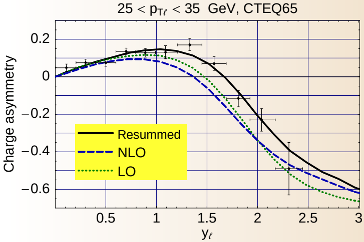
- constrains the PDF ratio $d(x, M_W)/u(x, M_W)$ at $x \to 1$
- In experimental analyses, a selection cut $p_{Te} > p_{Te}^{min}$ is imposed

Charge asymmetry in p_T^e bins (CDF Run-2)









- With p_{Te} cuts imposed, $A_{ch}(y_e)$ is sensitive to small-Q_T resummation

Factorization for inclusive cross sections

Scale dependence of the renormalized QCD charge $g(\mu)$ and fermion masses $m_f(\mu)$:

$$\mu \frac{dg(\mu)}{d\mu} = \beta(g(\mu)), \qquad \mu \frac{dm_f(\mu)}{d\mu} = -\gamma_m(g(\mu)) m_f(\mu)$$

The RG equations predict that $\alpha_s(\mu) \to 0$ and $m_f(\mu) \to 0$ as $\mu \to \infty$

These features are employed to prove factorization for inclusive Drell-Yan cross sections *(Bodwin, PRD 31, 2616 (1985); Collins, Soper, Sterman, NPB 261, 104 (1985); B308, 833 (1988))*:

$$\frac{d\sigma(Q,\{m_f\})}{d\tau} = \sum_{a,b} \int_{x_A}^{1} d\xi_A \int_{x_B}^{1} d\xi_B \frac{d\widehat{\sigma}\left(\frac{Q}{\mu}, \frac{\tau}{\xi_A \xi_B}, \{m_f = 0\}\right)}{d\tau} f_{a/A}(\xi_A,\mu) f_{b/B}(\xi_B,\mu)$$
$$+ \mathcal{O}\left(\left\{m_f^2/\mu^2\right\}\right)$$

assuming $\mu \sim Q \sim \sqrt{s} \gg \{m_f\}, \Lambda_{QCD}$

Factorization for inclusive cross sections

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- The hard cross section $\widehat{\sigma}$ is infrared-safe: $\lim_{\{m_f \to 0\}} \widehat{\sigma}(\{m_f\})$ is finite and can be computed as a series in $\alpha_s(\mu)$
- Collinear logarithms are subtracted from $\widehat{\sigma}$ and resummed in $f(\xi,\mu)$ using DGLAP equations
- Soft-gluon singularities in $\widehat{\sigma}$ vanish when the sum of all Feynman diagrams is integrated over all phase space (Kinoshita-Lee-Nauenberg theorem)

Factorization for Q_T distributions

- Differential distributions may still contain integrable soft singularities of the type $\alpha_s^k \ln^m(Q^2/p_i \cdot p_j)$, e.g., $L \equiv \ln(Q^2/Q_T^2) \gg 1$:

$$
\begin{aligned}
\left.\frac{d\sigma}{dQ_T^2}\right|_{Q_T\to 0} \quad \approx \quad & \frac{1}{Q_T^2}\Big\{ \\
& \alpha_S\,(L+1) \\
+ \quad & \alpha_S^2\left(L^3+L^2+L+1\right) \\
+ \quad & \alpha_S^3\left(L^5+L^4+L^3+L^2+L+1\right) \\
+ \quad & \ldots\Big\}.
\end{aligned}
$$

The purpose of Q_T resummation is to reorganize this series as

$$\left.\frac{d\sigma}{dQ_T^2}\right|_{Q_T\to 0} \approx \frac{1}{Q_T^2}\left\{\alpha_S Z_1 + \alpha_S^2 Z_2 + \ldots\right\},$$

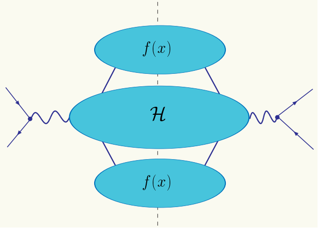
where $\alpha_S^{n+1} Z_{n+1} \ll \alpha_S^n Z_n$:

$$
\begin{array}{lcll}
\alpha_S Z_1 & \sim & \alpha_S(L+1) + \alpha_S^2(L^3+L^2) + \alpha_S^3(L^5+L^4) + \ldots & |\, A_1, B_1, \mathcal{C}_0\ ; \\
\alpha_S^2 Z_2 & \sim & \alpha_S^2(L+1) + \alpha_S^3(L^3+L^2) + \ldots & |\, A_2, B_2, \mathcal{C}_1\ ; \\
\alpha_S^3 Z_3 & \sim & \alpha_S^3(L+1) + \ldots & |\, A_3, B_3, \mathcal{C}_2\ . \\
 & \ldots & &
\end{array}
$$

QCD factorization at large and small Q_T

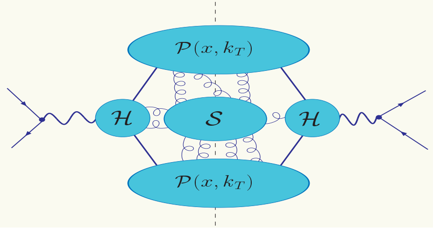
Finite-order (FO) factorization

$$\Lambda^2_{QCD} \ll q_T^2 \sim Q^2$$

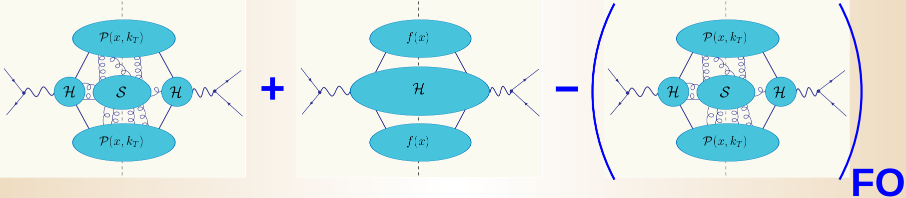


Small-q_T factorization

$$\Lambda^2_{QCD} \ll q_T^2 \ll Q^2$$



Solution for all q_T:



Factorization at $Q_T \ll Q$

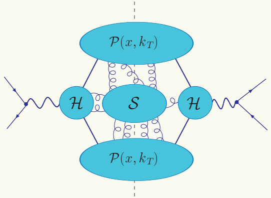
(Collins, Soper, Sterman, 1985)

Realized in space of the impact parameter b

$$\left.\frac{d\sigma_{AB\to VX}}{dQ^2 dy dq_T^2}\right|_{q_T^2 \ll Q^2} = \sum_{flavors} \int \frac{d^2 b}{(2\pi)^2} e^{-i\vec{q}_T\cdot\vec{b}} \widetilde{W}_{ab}(b, Q, x_A, x_B)$$

$$\widetilde{W}_{ab}(b, Q, x_A, x_B) = |\mathcal{H}_{ab}|^2 \; e^{-\mathcal{S}(b,Q)} \overline{\mathcal{P}}_a(x_A, b) \overline{\mathcal{P}}_b(x_B, b)$$

$\mathcal{H}_{ab}$ is the hard vertex, $\mathcal{S}$ is the soft (Sudakov) factor, $\overline{\mathcal{P}}_a(x, b)$ is the unintegrated PDF



For $b \ll 1$ GeV^{-1}, $\widetilde{W}_{ab}(b, Q, x_A, x_B)$ is calculable in perturbative QCD; at $Q \sim M_Z$, this region dominates the resummed cross section

Nonperturbative contributions at large b

At $b \gtrsim 1\ \text{GeV}^{-1}$, the leading nonperturbative contribution is approximated as $\exp\left(-a(Q)b^2\right)$, where $a(Q)$ is an effective "nonperturbative parton $\langle k_T^2 \rangle/4$" inside the proton

The RG invariance suggests that

$$a(Q) \approx a_1 + a_2 \ln Q,$$

where $a_{1,2} \sim \Lambda^2_{QCD}$, and a_2 is process-independent

The $\ln Q$ growth of $a(Q)$ is indeed observed in the Drell-Yan and Z p_T data

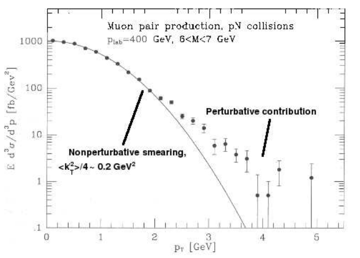
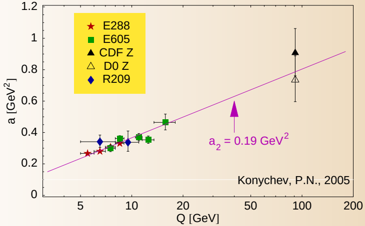
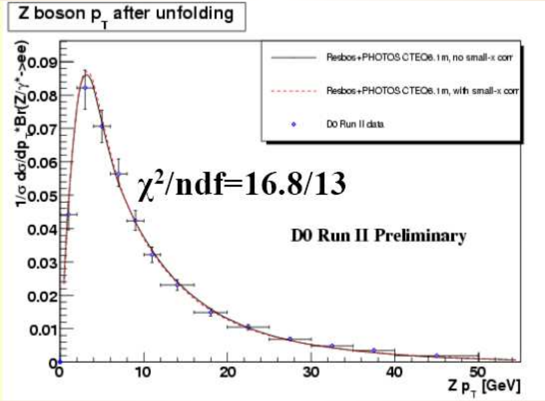


Fig. 9.2. The lepton pair transverse momentum from the CFS collaboration [4]. The curve corresponds to a Gaussian intrinsic k_T distribution for the annihilating



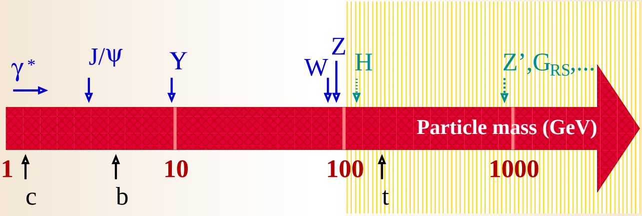
An example of the resummed cross section

Z production at the Tevatron vs. resummed NLO (*Balazs, Ladinsky, PN, Yuan)*



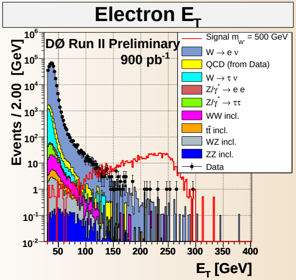
In this case, precise predictions for $d\sigma/dQ_T$ are needed to measure M_W with accuracy better than 0.03%

Particle states probed by Drell-Yan-like processes

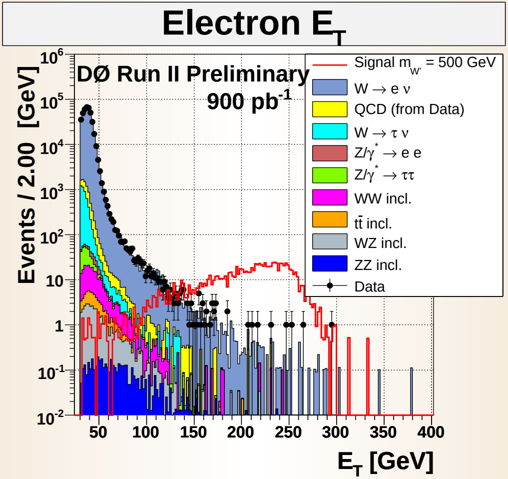


New physics at $Q > 100$ GeV

- Indirect constraints from electroweak precision measurements
- direct new physics searches

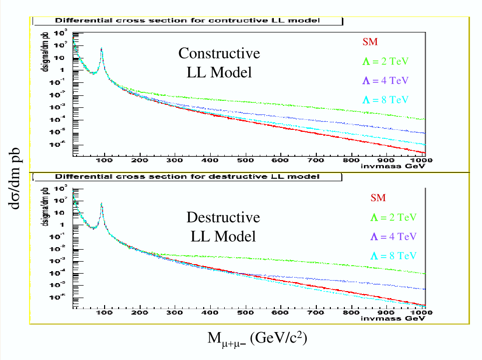


Search for heavy states at DO



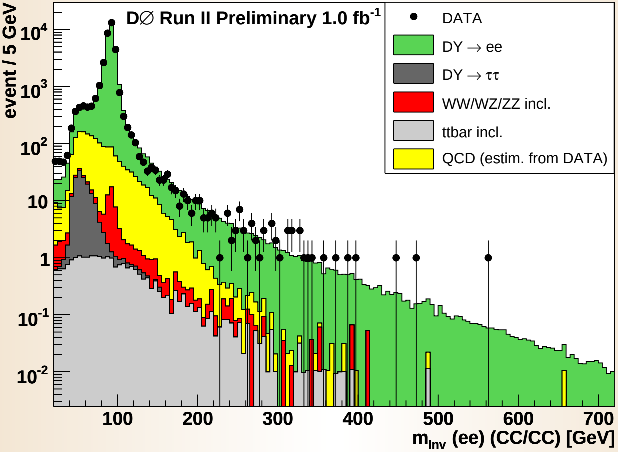
$$W' \to \ell\nu$$

Search for heavy states at DO



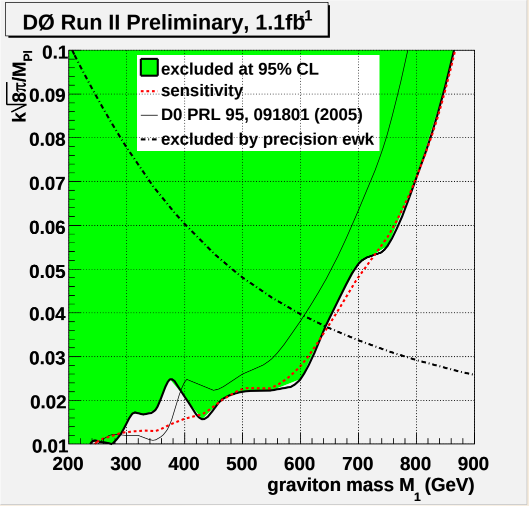
Leptoquark $\rightarrow \mu\mu$

Search for heavy states at DO



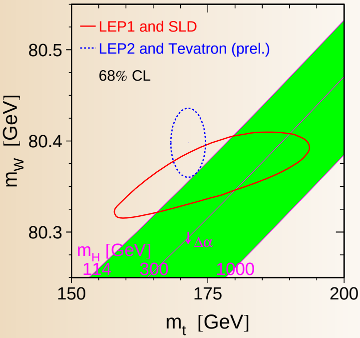
Contact interactions: $p\bar{p} \to e(e^* \to e\gamma)X$

Search for heavy states at DO



Randall-Sundrum graviton $\rightarrow ee, \gamma\gamma$

Higgs sector in Standard Model & supersymmetry



Green band: $114 \leq M_H \leq 1000$ GeV

SM: 1 Higgs doublet, one boson H

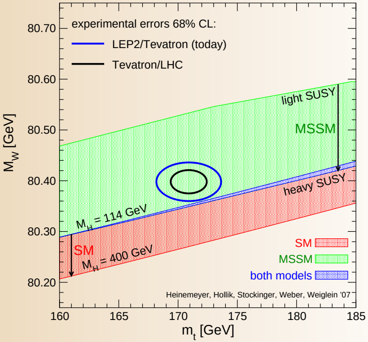
- Direct search: $m_H > 114$ GeV at 95% c.l.
- indirect: $M_H = 80^{+39}_{-28}$ GeV at 68% c.l.

MSSM: 2 Higgs doublets; $h^0, H^0, A^0, H^\pm$

$m_h \leq m_Z|\cos 2\beta| +$ rad. corr. $\lesssim 135$ GeV

- In these models, expect one or more Higgs bosons with mass below 140 GeV
- Many other possibilities for EW symmetry breaking exist!

Higgs sector in Standard Model & supersymmetry



SM band: $114 \leq M_H \leq 400$ GeV
SUSY band: random scan

- the goal of direct and indirect measurements is to over-constrain SM, greatly constrain SUSY
- indirect constraints strongly depend on M_W, m_t values, hence require accurate QCD predictions for W and t production

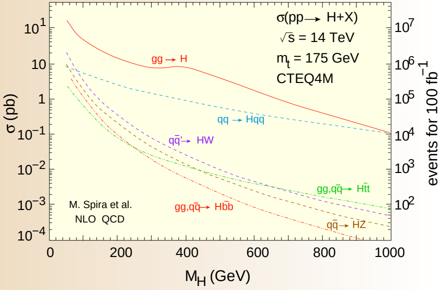
For example, in SM

$$M_W = 80.3827 - 0.0579 \ln\left(\frac{M_H}{100\text{ GeV}}\right) - 0.008 \ln^2\left(\frac{M_H}{100\text{ GeV}}\right)$$

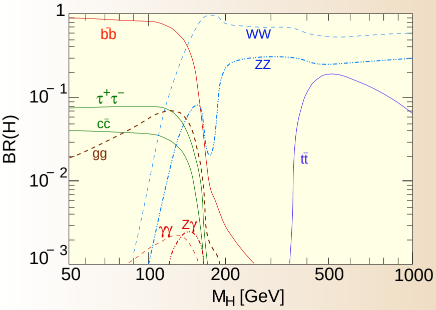
$$+0.543\left(\left(\frac{m_t}{175\text{ GeV}}\right)^2 - 1\right) - 0.517\left(\frac{\Delta\alpha_{had}^{(5)}(M_Z)}{0.0280} - 1\right) - 0.085\left(\frac{\alpha_s(M_Z)}{0.118} - 1\right)$$

SM Higgs boson search at the LHC

Production rate

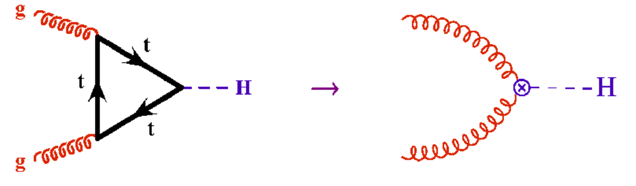


Branching ratios



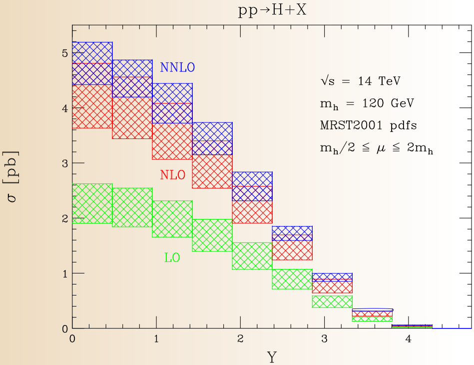
Let's concentrate on $gg \to H \to \gamma\gamma$, the leading search mode for $M_H < 140$ GeV (besides vector boson fusion and $t\bar{t}H$ production)

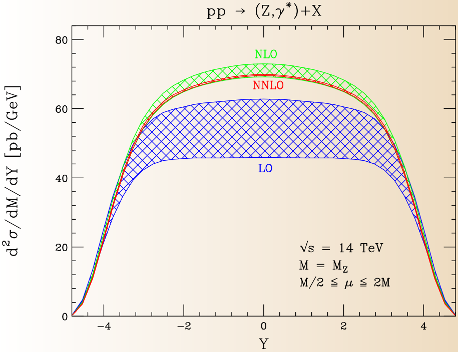
$gg \to$ Higgs $\to \gamma\gamma$



The scattering proceeds via a top quark loop, which can be replaced by an effective point vertex under the assumption $m_t^2 \gg m_H^2$ (works well for $m_H \lesssim 350$ GeV). This trick greatly simplifies calculations, which can be carried out up to two gluon loops (as in the Drell-Yan process). Many techniques developed for the Drell-Yan process also apply to Higgs production

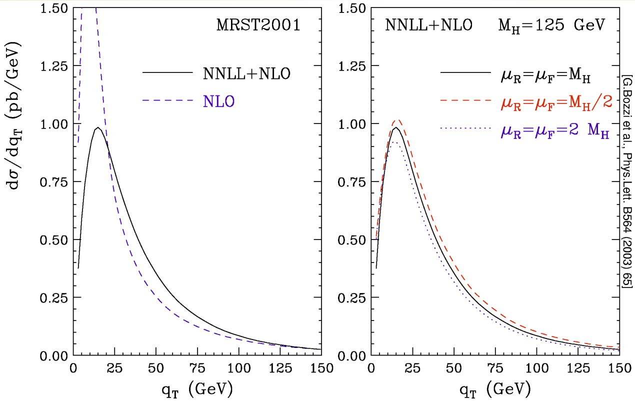
Scale dependence of rapidity distributions





However, $gg \to$ Higgs is characterized by slower convergence of the series in α_s than $q\bar{q} \to W, Z$

Q_T Resummation



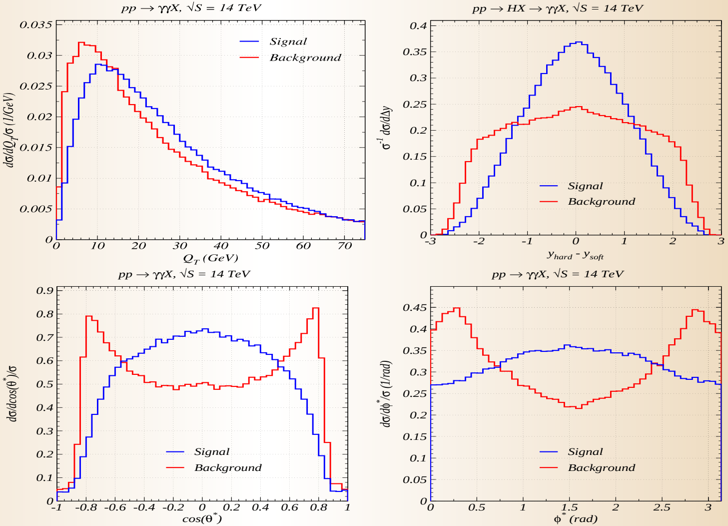
Q_T resummation for Higgs bosons has been carried out by several groups, and they are in a reasonable agreement *(Balazs, Yuan; Berger, Qiu; Bozzi et al.; Kulesza, Stirling; Kulesza, Sterman, Vogelsang)*

Resummed distributions for Higgs $\to \gamma\gamma$ signal and background (ResBos, normalized; $M_H = 130$ GeV, $128 < Q < 132$ GeV)

Q_T and $y_{\gamma_1} - y_{\gamma_2}$ in the lab frame

Decay angles θ_*, φ_* in the $\gamma\gamma$ rest frame

no singularities, in contrast to the fixed-order rate



Summary

Essential applications of Drell-Yan-like processes

- clean tests of QCD factorization
- studies of the nucleon structure (quark sea, flavor separation,...)
- "standard candle" processes (luminosity monitors....)
- electroweak precision measurements
- searches for new physics

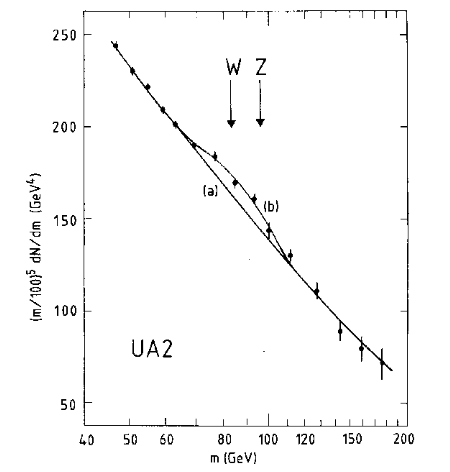
Many interesting topics were not covered

- Polarized Drell-Yan-like processes (measurements of new nucleon structure functions)
- Connections to k_T factorization in semi-inclusive DIS
- Various resummations (small x, threshold, heavy-quark....)
- Higher-twist and nuclear effects in low-Q Drell-Yan and heavy-ion scattering

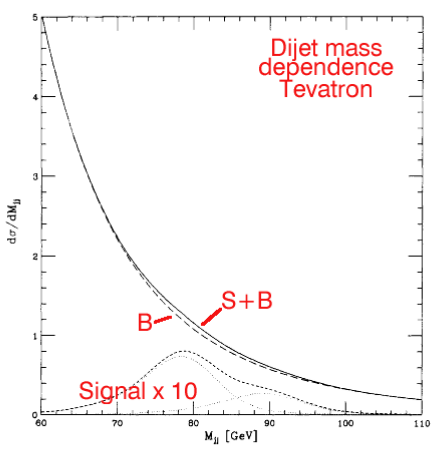
Many exciting studies still remain to be done!

Backup slides

W and Z signal in the hadron decay mode at SPS and Tevatron

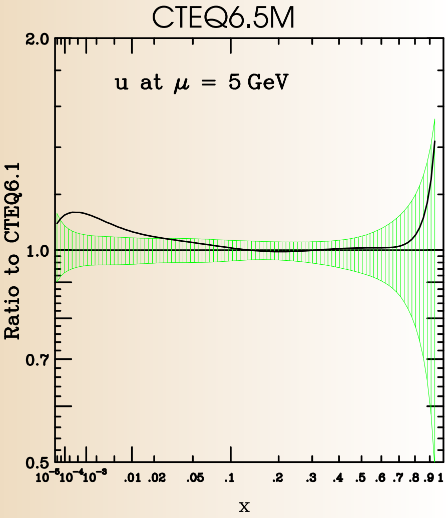


$pp \to$ jets at $\sqrt{s} = 630$ GeV; background/signal~20



$p\bar{p} \to$ jets at $\sqrt{s} = 1.8$ TeV; background/signal~255 *(J. Pumplin, PRD45, 806 (1992))*

Impact of charm contributions to DIS at HERA



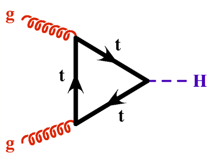
CTEQ6.5 employs a more accurate calculation of charm mass effects (general-mass factorization scheme) in DIS structure functions $F_i(x, Q^2)$ at HERA

- W, Z production at the LHC: $x \sim 10^{-3} - 10^{-2}$
- Suppression of charm contribution to $F_2(x, Q^2)$ in CTEQ6.5 results in larger $\overset{(-)}{u}(x)$, $\overset{(-)}{d}(x)$ at small $x \Rightarrow$ larger $\sigma_{W,Z}^{LHC}$

$$\delta\bar{q}_{light}(x)/\bar{q}_{light}(x) = 3-4\% \quad \Rightarrow \quad \delta\mathcal{L}_{q_i\bar{q}_j}/\mathcal{L}_{q_i\bar{q}_j} = 2(\delta\bar{q}_{light}/\bar{q}_{light}) = 6-8\%$$

Heavy Quark Loops

Somewhat surprisingly, gluon fusion via a virtual top-quark loop dominates Higgs production at hadron colliders.

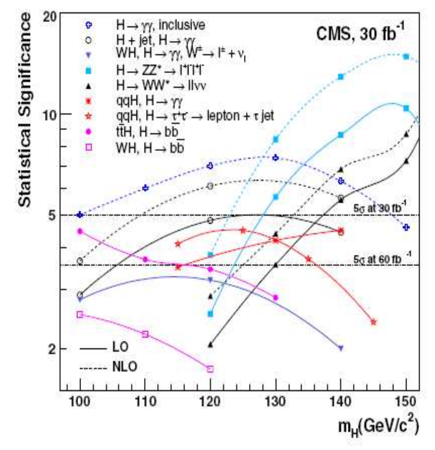


$$\sigma_{\rm LO}(gg \to H) = \frac{\pi G_{\rm F}}{128\sqrt{2}} \left(\frac{\alpha_s(\mu)}{\pi}\right)^2 \tau^2 \left|1 + (1-\tau) f(\tau)\right|^2 \delta\left(1 - \frac{M_H^2}{\hat{s}}\right)$$

$$f(\tau) = \begin{cases} \arcsin^2 \frac{1}{\sqrt{\tau}}, & \tau \geq 1, \\ -\frac{1}{4}\left[\ln \frac{1+\sqrt{1-\tau}}{1-\sqrt{1-\tau}} - i\pi\right]^2, & \tau < 1, \end{cases} \qquad \tau = 4M_t^2/M_H^2,$$

Light Higgs boson search at the LHC

- $gg \to h \to \gamma\gamma$ (via a t-quark loop) is the leading search mode for $115 \lesssim M_H \lesssim 140$ GeV
- A 5σ discovery of SM Higgs boson is possible with $\mathcal{L} = 10 - 30$ fb^{-1}
- $\delta M_H \lesssim 1$ GeV, $\delta\sigma(H \to \gamma\gamma) \sim 20\%$ within the experimental reach at later stages?



Light Higgs boson search at the LHC

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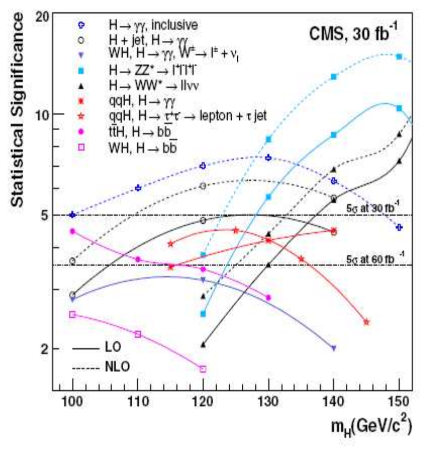
- $\delta M_H \lesssim 1$ GeV, $\delta\sigma(H \to \gamma\gamma) \sim 20\%$ within the experimental reach at later stages?
- Statistical significance depends on the (new) physics model, QCD contributions, etc.



A challenging measurement!