Vector boson production in hadron-hadron scattering

(Drell-Yan-like processes)

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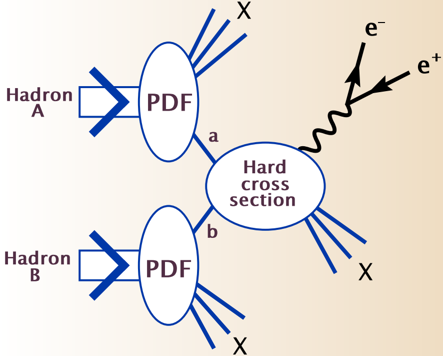
DY-like processes: $A(p_A)B(p_B) \to (V(q) \to v_1 v_2 ...)X$

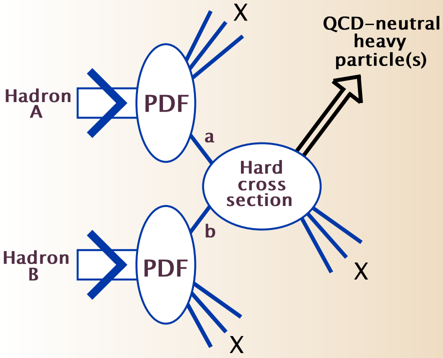


Drell-Yan production of lepton pairs

DY-like processes: $A(p_A)B(p_B) \to (V(q) \to v_1 v_2 ...)X$

Notations

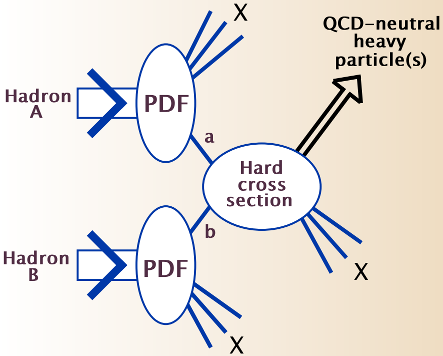
- A,B – initial-state hadrons (p, $\bar{p}$, n, nuclei, π, ...)
- V – a final-state QCD-neutral system (a vector boson or boson pair with mass $Q \gg \Lambda_{QCD}$)
- v_1, v_2– observed particles from decay of V (e.g., leptons)



DY-like processes: $A(p_A)B(p_B) \to (V(q) \to v_1 v_2 ...)X$

DY-like processes are ubiquitous

- $AB \to (\gamma^*, Z \to \ell^+\ell^-)X$ (with $\ell = e, \mu$)
- $AB \to (W \to \ell\nu_\ell)X$
- $AB \to VVX$ (with $V = \gamma, W, Z, ...$)
- $AB \to$ Higgs $+ X$ (F. Petriello)
- $AB \to V_{BSM}X$ (with $V_{BSM} = Z'$, Randall-Sundrum graviton, etc.)



DY-like processes: $A(p_A)B(p_B) \to (V(q) \to v_1 v_2 ...)X$

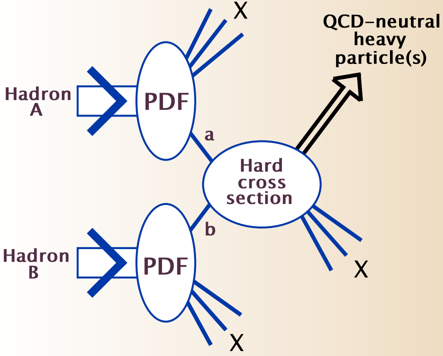
DY-like processes are "simple"

- V does not interact with final-state hadrons, which are summed over in cross sections

  $\Rightarrow$ no dependence on final-state nonperturbative functions

- QCD factorization is **proved** to all orders in α_s for a number of DY observables

  ▶ (In many other processes, factorization is only a **plausible conjecture**)



DY-like processes: $A(p_A)B(p_B) \to (V(q) \to v_1 v_2 ...)X$

Example: factorization for the total cross section

$$\frac{d\sigma}{dQ^2} = \sum_{a,b} \int_\tau^1 \frac{d\xi}{\xi} f_{a/A}(\xi, Q) f_{b/B}(\frac{\tau}{\xi}, Q) \frac{d\widehat{\sigma}_{ab}}{dQ^2},$$

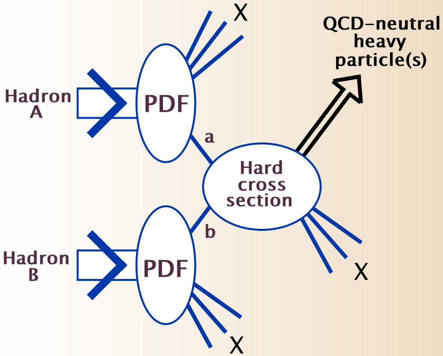
where

Q is the invariant mass of V;

$\tau \equiv Q^2/s$;

$\widehat{\sigma}_{ab}$ is the hard-scattering cross section (calculated as a series in the QCD coupling α_s);

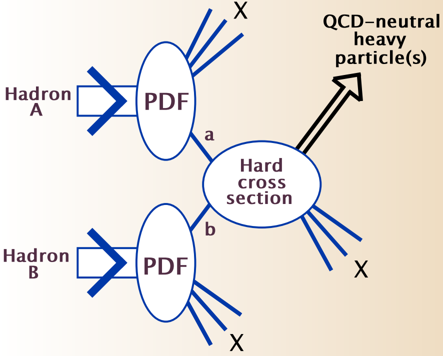
$f_{a/A}(\xi, \mu)$ and $f_{b/B}(\tau/\xi, \mu)$ are parton distribution functions



DY-like processes: $A(p_A)B(p_B) \to (V(q) \to v_1 v_2 ...)X$

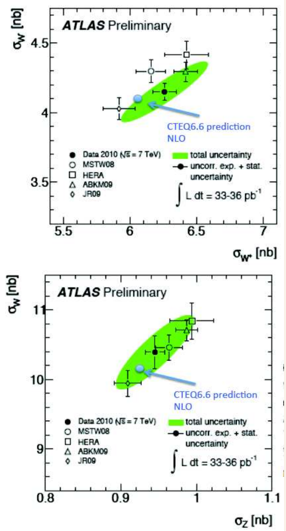
DY-like processes produced many important discoveries

- early confirmation of the parton model
- discovery of heavy quarks (which ones?)
- discovery of massive carriers of weak force (W and Z)



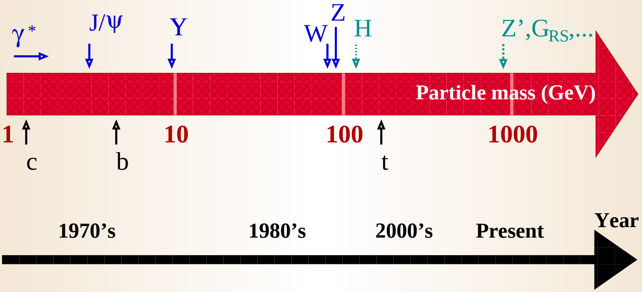
Modern DY experiments provide most precise QCD tests at hadron colliders

W and Z cross sections at the LHC



Measurement of σ_W and σ_Z confirms the validity of perturbative QCD at $\sqrt{s} = 7$ TeV

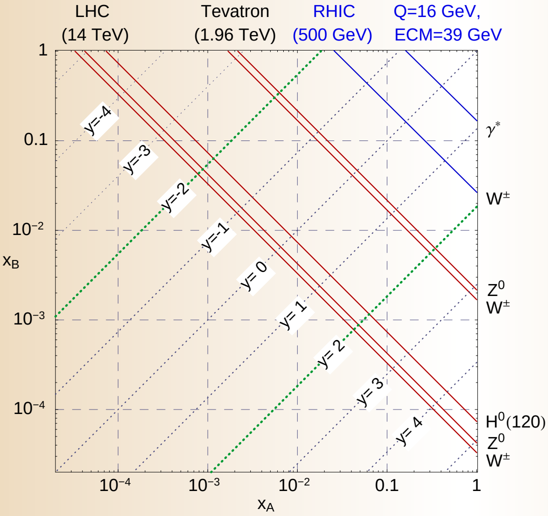
Final states in DY-like processes



Explore the DY-like processes as a function of $Q \equiv M_{\ell\ell'}$, the invariant mass of the heavy EW state

$$\frac{d\sigma}{dQ^2} = \sum_{a,b} \int_\tau^1 \frac{d\xi}{\xi} f_{a/A}(\xi, Q) f_{b/B}(\frac{\tau}{\xi}, Q) \frac{d\widehat{\sigma}_{ab}}{dQ^2}$$

Typical parton momentum fractions



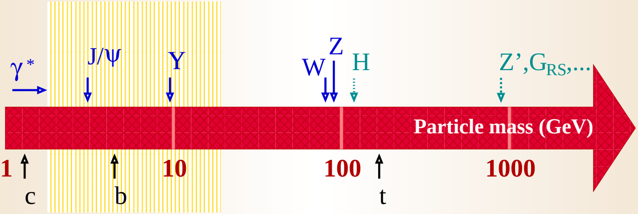
$$x_{A,B} \equiv \frac{Q}{\sqrt{s}} e^{\pm y}$$

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

Final states in DY-like processes



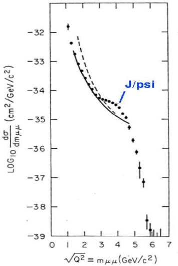
$pN \xrightarrow{\gamma^*} \ell^+\ell^- X$ at $Q < 20$ GeV

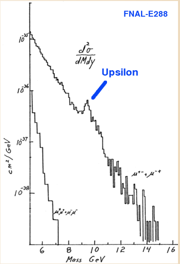
- Continuous γ^* cross section
- Multiple quarkonium resonances

(studied by non-relativistic QCD, **not** in the PDF fit)

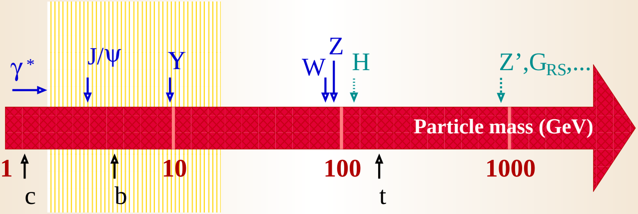
▲ J/ψ ($c\bar{c}$)– found in e^+e^- scattering (1974)

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

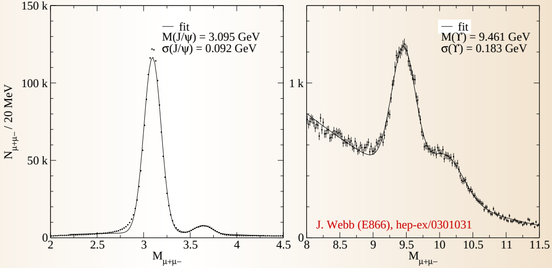




Final states in DY-like processes



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

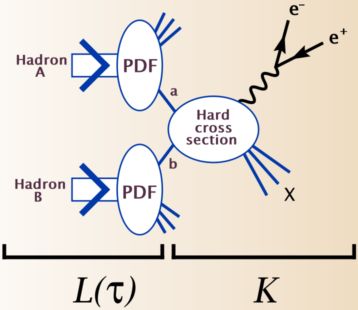


Scaling of the continuum cross section

S. Drell, T. M. Yan, 1970

$$s\frac{d\sigma}{dQ^2} \approx \mathcal{L}_{ab}(\tau) \cdot \text{const}$$

- $\mathcal{L}_{ab}(\tau)$ is the "parton luminosity", originally derived from DIS functions; depends only on τ if the $\ln Q$ dependence is neglected



Scaling of the continuum cross section

S. Drell, T. M. Yan, 1970

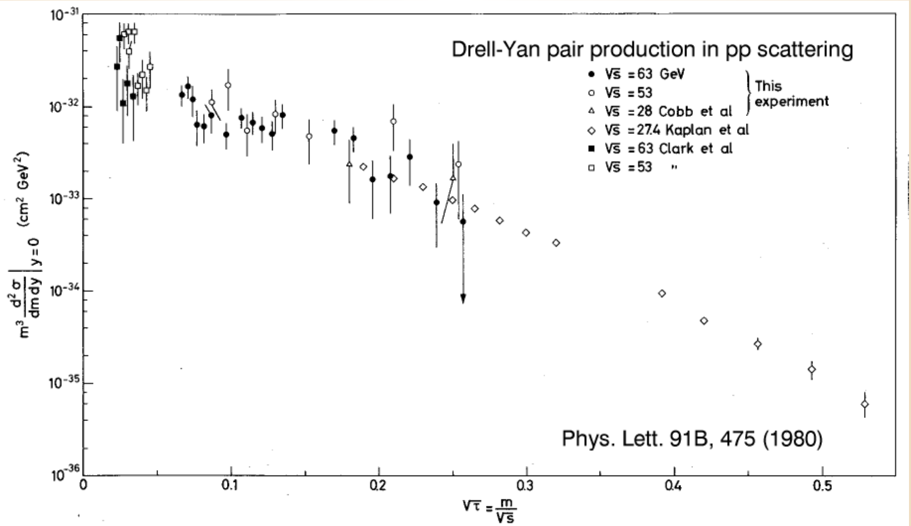
$$s\frac{d\sigma}{dQ^2} \approx \mathcal{L}_{ab}(\tau)\cdot \text{const}$$

- Compare to the Born cross section:

$$\left(\frac{d\sigma}{dQ^2}\right)_{LO} = \frac{4\pi\alpha_{EM}^2}{3N_c Q^2 s}$$
$$\times \underbrace{\sum_{i=u,d,s,\dots} e_i^2 \int_\tau^1 \frac{d\xi}{\xi}\left[f_{q_i/A}(\xi,Q) f_{\bar{q}_i/B}(\frac{\tau}{\xi},Q) + f_{\bar{q}_i/A}(\xi,Q) f_{q_i/B}(\frac{\tau}{\xi},Q)\right]}_{\mathcal{L}(\tau)},$$

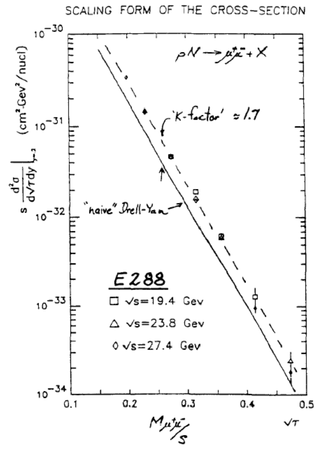
with $N_c = 3$, $\alpha_{EM} \equiv e^2/(4\pi)$, ee_i is the fractional quark charge

Scaling of the low-Q data



NLO corrections and the K-factor

Tau-scaling works because radiative corrections to $q\bar{q} \to VX$ are relatively constant at $x \sim 0.1$



A useful estimate

$$\frac{d\sigma}{dQ^2} \approx \left(\frac{d\sigma}{dQ^2}\right)_{LO} (\tau) \cdot K_{NLO}(Q),$$

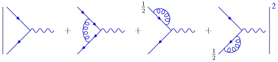
where $K_{NLO} = 1 + \kappa\alpha_s(Q)$ with $\kappa = 3 \pm 1$

(also applies to W, Z, ... production)

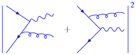
Exercise: show that $K \approx 1.65$ (1.35) at $Q = 5$ (90) GeV

NLO cross section

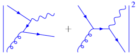
- NLO: $(\alpha_s^{(1)})$ virtual corrections $(q\overline{q'})_{virt}$



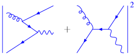
- NLO: $(\alpha_s^{(1)})$ real emission diagrams $(q\overline{q'})_{real}$



- NLO: $(\alpha_s^{(1)})$ real emission diagrams $(qG)_{real}$



- NLO: $(\alpha_s^{(1)})$ real emission diagrams $(G\overline{q'})_{real}$



Virtual contributions

The dominant contribution to σ_{tot}, if x is moderate

$$\sigma_{tot}^{NLO} \sim \left[1 + \frac{\alpha_s}{2\pi} C_F \left(1 + \frac{4\pi^2}{3}\right)\right] \sigma_{tot}^{LO}$$
$$\sim \left[1 + 3.005\alpha_s\right] \sigma_{tot}^{LO}$$

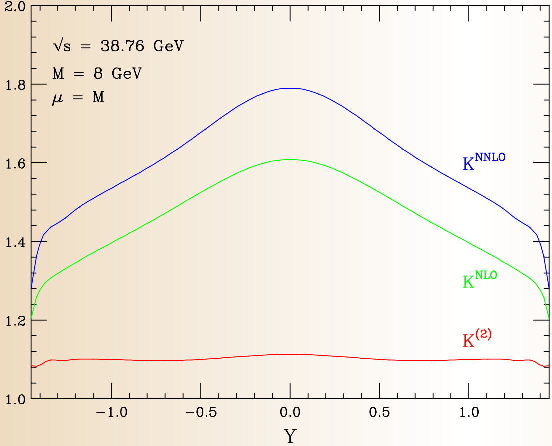
At $x \to 0$ or 1, $ln(x)$ or $ln^p(1-x)/(1-x)_+$ terms are enhanced; the NLO factor is not constant!

$2 \to 3$ contributions

Generate $Q_T \neq 0$, non-trivial θ_*, φ_* dependence

NNLO cross sections for low-Q DY process

Anastasiou, Dixon, Melnikov, Petriello, 2003-05



$K^{NLO} \approx 1.6$ at $y = 0$

$K^{NLO} \approx 1.4$ at $y = 1$

Compare with $1 + 3\alpha_s(8) \approx 1.56$

$K^{(2)} = \sigma_{NNLO}/\sigma_{NLO}$ – uniform enhancement over NLO by $\sim 8\%$

Classical measurements in low-Q DY process

1. Sea quark PDFs $\bar{q}_i(x, Q)$ from rapidity (y) distributions
2. Spins of γ^* and quarks from angular distributions of decay leptons

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

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

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

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

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

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

If deuterium binding corrections are neglected:

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

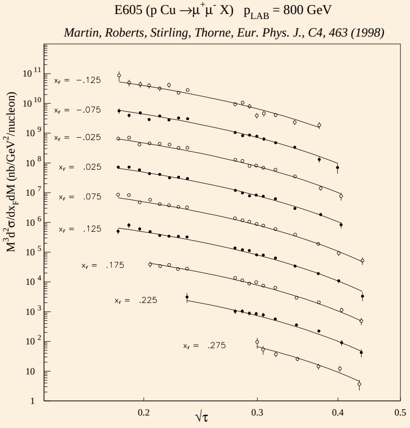
At $x_A \gg x_B$ (large y): $\bar{q}(x_A) \sim 0$ and $4u(x_A) \gg d(x_A)$

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

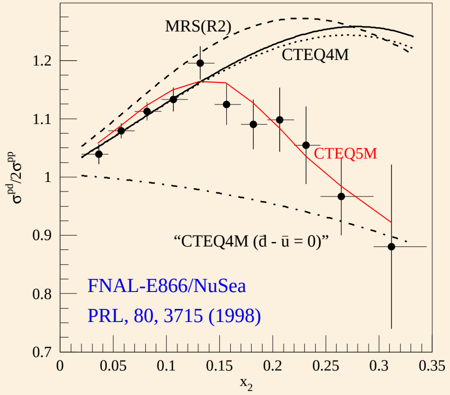
$\therefore \sigma_{pd}/(2\sigma_{pp})$ constrains $\bar{d}(x, Q)/\bar{u}(x, Q)$ at moderate x

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 $\bar{d}/\bar{u}$

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

2. Lepton distributions in the rest frame of γ^*

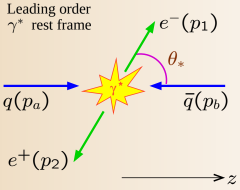
The Born cross section for $q_j \bar{q}_{\bar{k}} \rightarrow V \rightarrow \ell \bar{\ell}'$ is derived tomorrow:

$$\frac{d\sigma}{dQ^2 dy d\Omega} \propto$$

$$\times \sum_{j,\bar{k}=u,\bar{u},d,\bar{d},\ldots} \Big\{ (f_R^2 + f_L^2)(g_{L,j\bar{k}}^2 + g_{R,j\bar{k}}^2)(1+\cos^2\theta_*)\,[q_j(x_A)\bar{q}_{\bar{k}}(x_B) + \bar{q}_{\bar{k}}(x_A) q_j(x_B)]$$

$$+(f_R^2 - f_L^2)(g_{L,j\bar{k}}^2 - g_{R,j\bar{k}}^2)(2\cos\theta_*)\,[q_j(x_A)\bar{q}_{\bar{k}}(x_B) - \bar{q}_{\bar{k}}(x_A) q_j(x_B)] \Big\}$$

- f_L, f_R are left-handed and right-handed $V\ell\bar{\ell}'$ couplings
- $g_{L,j\bar{k}}$, $g_{R,j\bar{k}}$ are left-handed and right-handed $V q_j \bar{q}_{\bar{k}}$ couplings



The E, p_x, p_y, p_z components are

$$p_a = \frac{Q}{2}(1,0,0,1);\; p_b = \frac{Q}{2}(1,0,0,-1);$$

$$p_1 = \frac{Q}{2}(1,0,0,\cos\theta_*);\; p_2 = \frac{Q}{2}(1,0,0,-\cos\theta_*);$$

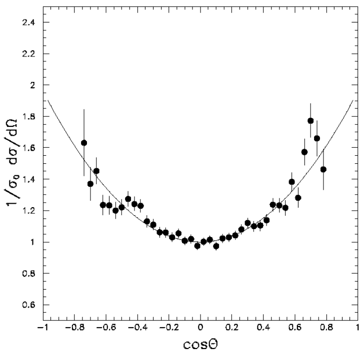
The Born cross section

$$\frac{d\sigma}{dQ^2 dy d\Omega} \propto$$

$$\times \sum_{j,\bar{k}=u,\bar{u},d,\bar{d},\ldots} \Big\{ (f_R^2 + f_L^2)(g_{L,j\bar{k}}^2 + g_{R,j\bar{k}}^2)(1+\cos^2\theta_*)\,[q_j(x_A)\bar{q}_{\bar{k}}(x_B) + \bar{q}_{\bar{k}}(x_A) q_j(x_B)]$$

$$+ (f_R^2 - f_L^2)(g_{L,j\bar{k}}^2 - g_{R,j\bar{k}}^2)(2\cos\theta_*)\,[q_j(x_A)\bar{q}_{\bar{k}}(x_B) - \bar{q}_{\bar{k}}(x_A) q_j(x_B)] \Big\}$$

- The $2\cos\theta_*$ term vanishes in the parity-conserving case ($f_L = f_R$ or $g_L = g_R$)
- The $(1+\cos\theta_*^2)$ dependence in the experimental data confirms the vector (spin-1) nature of low-Q Drell-Yan process



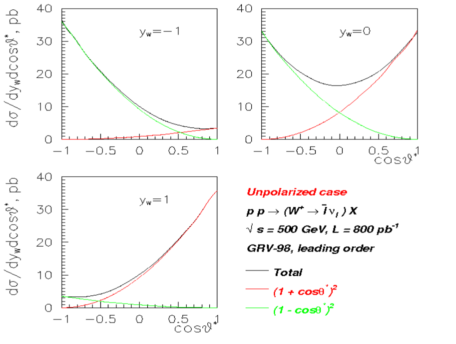
The Born cross section

$$\frac{d\sigma}{dQ^2 dy d\Omega} \propto$$

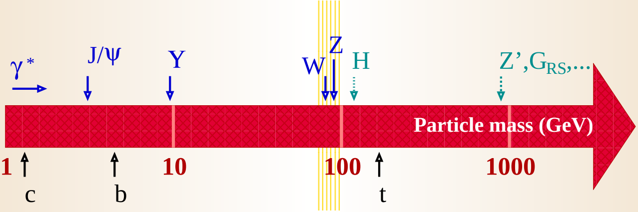
$$\times \sum_{j,\bar{k}=u,\bar{u},d,\bar{d},\dots} \Big\{ (f_R^2 + f_L^2)(g_{L,j\bar{k}}^2 + g_{R,j\bar{k}}^2)(1+\cos^2\theta_*) \left[q_j(x_A)\bar{q}_{\bar{k}}(x_B) + \bar{q}_{\bar{k}}(x_A) q_j(x_B) \right]$$

$$+(f_R^2 - f_L^2)(g_{L,j\bar{k}}^2 - g_{R,j\bar{k}}^2)(2\cos\theta_*) \left[q_j(x_A)\bar{q}_{\bar{k}}(x_B) - \bar{q}_{\bar{k}}(x_A) q_j(x_B) \right] \Big\}$$

- W boson production: $f_R = g_R = 0$
- W cross section depends on two functions $(1 \pm \cos\theta_*)^2$ weighted by different parton luminosities
- non-trivial correlation between y and θ_* in the acceptance, etc.

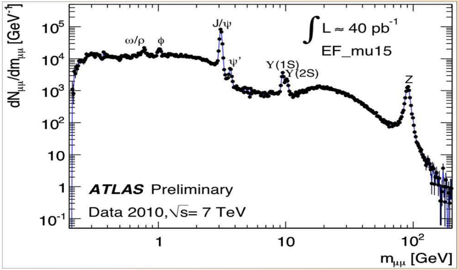


Final states in DY-like processes



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



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 are hard to observe because of the large background from QCD jets

The most 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 $\not{E}_T$

W and Z observables

- **Total cross sections**

$$\sigma_Z = \int \frac{d\sigma\left(pp \to (Z \to e^+e^-)X\right)}{d\vec{p}_{e^+} d\vec{p}_{e^-}} d\vec{p}_{e^+} d\vec{p}_{e^-}$$

- **Rapidity distributions and asymmetries**

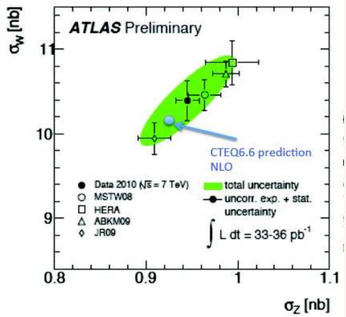
$$\frac{d\sigma_{W,Z}}{dQ^2 dy}, \text{ etc.}$$

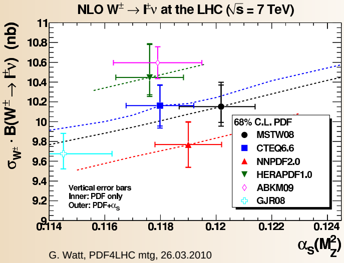
- **W boson mass M_W**

- **Transverse momentum and related distributions**

$$\frac{d\sigma_{W,Z}}{dQ_T^2}, \frac{d\sigma_{W,Z}}{d(p_T^e)^2}, \frac{d\sigma_{W,Z}}{d\left(M_T^{\ell\nu}\right)^2}$$

Total W and Z cross sections





Provide tests of perturbative QCD and collider luminosity with accuracy 3-5%

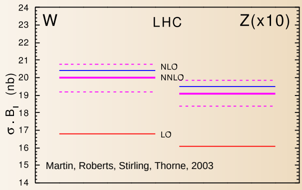
Require understanding of

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

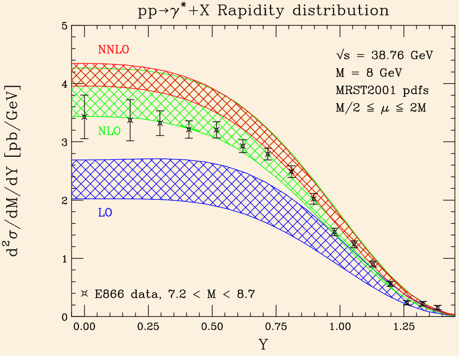
NNLO total section $\sigma_{tot}(AB \to W, Z)$

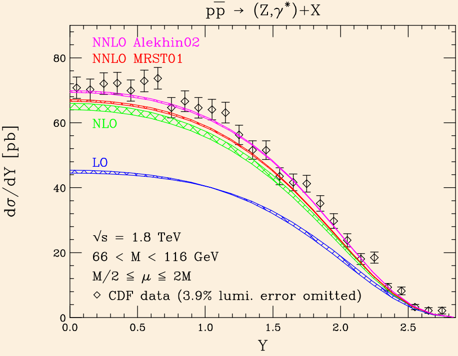
(Hamberg, van Neerven, Matsuura; Harlander, Kilgore)

- Scale dependence of order 1%
- NNLO K-factor is about 1.04 at the Tevatron and 0.98 at the LHC *(MRST'03)*

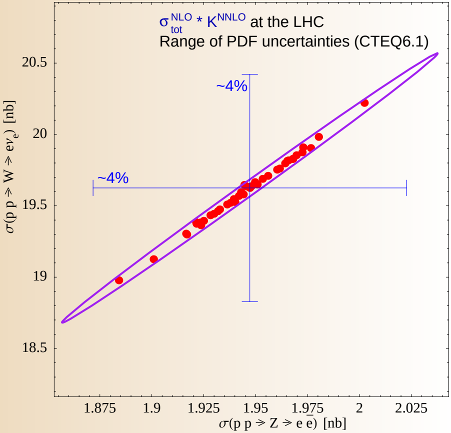


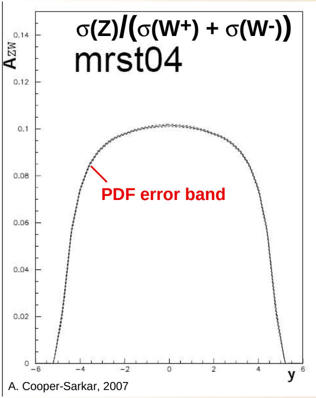
NNLO differential cross sections *(Anastasiou, Dixon, Melnikov, Petriello, 2003-05)*





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

W and Z observables

- Total cross sections

$$\sigma_Z = \int \frac{d\sigma\left(pp \rightarrow (Z \rightarrow e^+e^-)X\right)}{d\vec{p}_{e^+}d\vec{p}_{e^-}} d\vec{p}_{e^+}d\vec{p}_{e^-}$$

- **Rapidity distributions and asymmetries**

$$\frac{d\sigma_{W,Z}}{dQ^2dy}, \text{ etc.}$$

- W boson mass M_W

- Transverse momentum and related distributions

$$\frac{d\sigma_{W,Z}}{dQ_T^2}, \frac{d\sigma_{W,Z}}{d(p_T^e)^2}, \frac{d\sigma_{W,Z}}{d\left(M_T^{\ell\nu}\right)^2}$$

Charged lepton asymmetry at the Tevatron

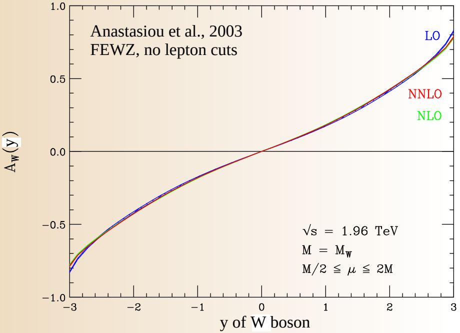
$$A_{ch}(y_e) \equiv \frac{\frac{d\sigma^{W^+}}{dy_e} - \frac{d\sigma^{W^-}}{dy_e}}{\frac{d\sigma^{W^+}}{dy_e} + \frac{d\sigma^{W^-}}{dy_e}}$$

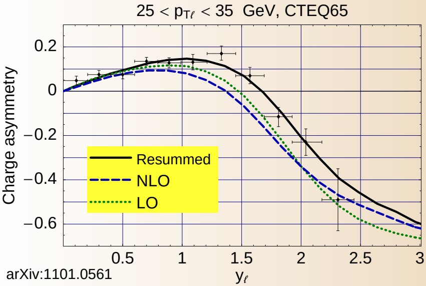
- related to the boson Born-level asymmetry when y_e is large

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

- 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

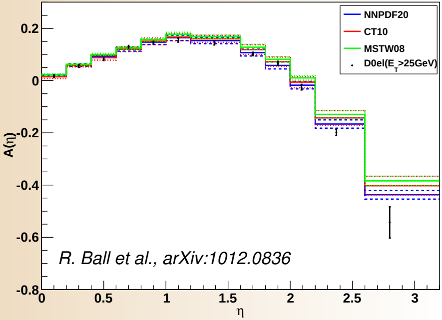
Charge asymmetry in p_T^e bins (CDF Run-2)

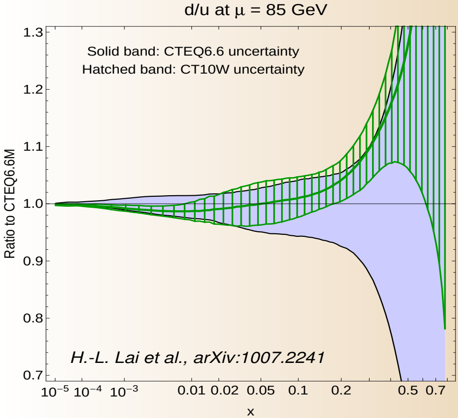




- Without p_{Te} cuts, $A_{ch}(y_e)$ is not sensitive to radiative contributions
- With p_{Te} cuts, $A_{ch}(y_e)$ is sensitive to small-Q_T resummation

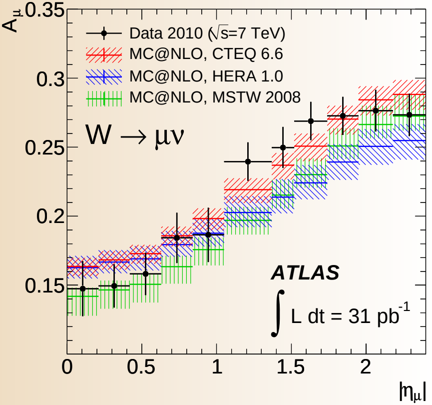
Impact of the Tevatron A_{ch} data on PDFs

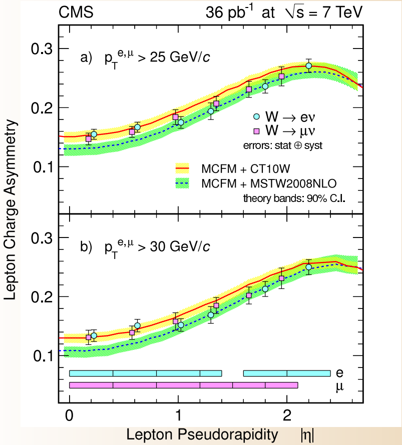




- The A_{ch} data distinguish between the PDF models, reduce the PDF uncertainty
- Very precise data! $\Rightarrow$ Many subtleties in their analysis

Charge asymmetry at the LHC





Sensitive both to d/u at $x > 0.1$ **and** $\bar{u}/\bar{d}$ at $x \sim 0.01$ (not constrained well by other experiments)

W and Z observables

- Total cross sections

$$\sigma_Z = \int \frac{d\sigma\left(pp \rightarrow (Z \rightarrow e^+e^-)X\right)}{d\vec{p}_{e^+} d\vec{p}_{e^-}} d\vec{p}_{e^+} d\vec{p}_{e^-}$$

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- **W boson mass M_W**

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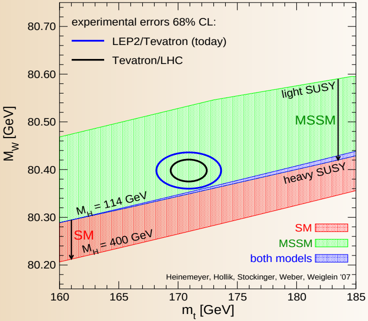
$$\frac{d\sigma_{W,Z}}{dQ_T^2}, \frac{d\sigma_{W,Z}}{d(p_T^e)^2}, \frac{d\sigma_{W,Z}}{d\left(M_T^{\ell\nu}\right)^2}$$

Constraints on the Higgs sector and W boson mass M_W

Both the Tevatron and LHC measure M_W. It provides key constraints on Higgs mass M_H in electroweak fits.

In SM:

$$M_W = 80.3827 - 0.0579 \ln\left(\frac{M_H}{100\text{ GeV}}\right) - 0.008 \ln^2\left(\frac{M_H}{100\text{ GeV}}\right)$$
$$+0.543\left(\left(\frac{m_t}{175\text{ GeV}}\right)^2 - 1\right) - 0.517\left(\frac{\Delta\alpha^{(5)}_{had}(M_Z)}{0.0280} - 1\right) - 0.085\left(\frac{\alpha_s(M_Z)}{0.118} - 1\right)$$



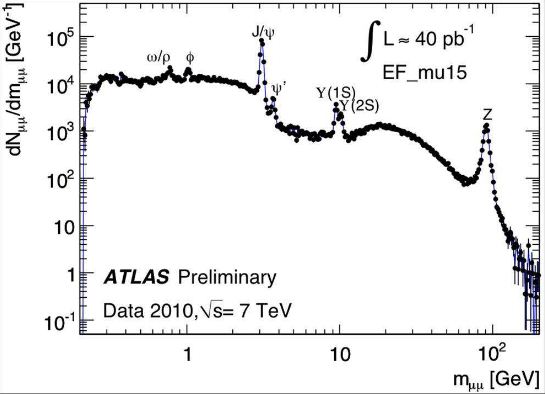
SM band: $114 \le M_H \le 400$ GeV
SUSY band: random scan

To know M_H to better than ± 50 GeV (50%) from the fit, M_W must be measured to better than ± 0.030 GeV (0.03%) – the accuracy that is already reached!

Question to the audience

In $p\bar{p} \to (Z \to \mu^+\mu^-)X$, the value of M_Z is found from the resonance in $d\sigma/dM_{\mu^+\mu^-}$

But in $p\bar{p} \to (W \to \ell\nu)X$, $d\sigma/dM_{\ell\nu}$ is not observed, because the ν's longitudinal momentum $p_{\nu 3}$ is not measured!

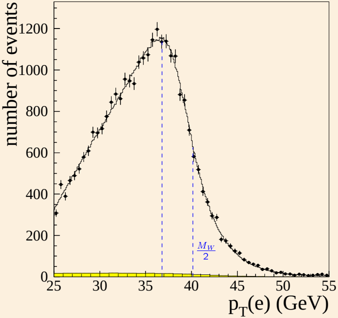


In this situation, which trick is used to measure M_W?

Jacobian peaks in distributions of decay leptons

Certain distributions contain a quasi-resonance (the Jacobian peak) that indicates the value of M_W

Electron's transverse momentum p_T^e



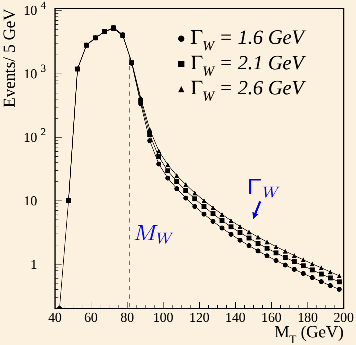
Jacobian peak at
$p_T^e = M_W/2 \approx 40$ GeV

Jacobian peaks in distributions of decay leptons

Certain distributions contain a quasi-resonance (the Jacobian peak) that indicates the value of M_W

Leptonic transverse mass $M_T^{e\nu}$

(Smith, van Neerven, Vermaseren, 1983)



$$M_T^{e\nu} \equiv 2(p_T^e p_T^\nu - \vec{p}_T^e \cdot \vec{p}_T^\nu)$$

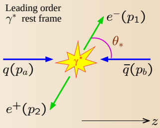
Jacobian peak at $M_T^{e\nu} = M_W$

The origin of the Jacobian peak

In the 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)

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

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

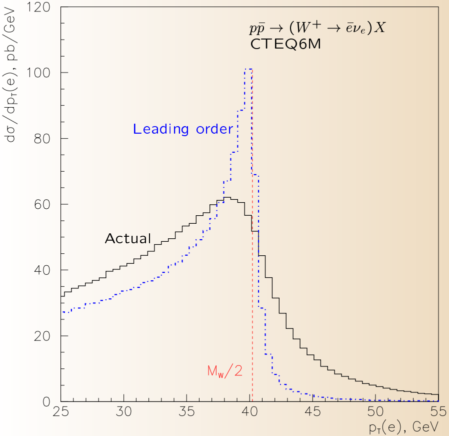
The origin of the Jacobian peak

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

(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 $Q_T \ll Q$



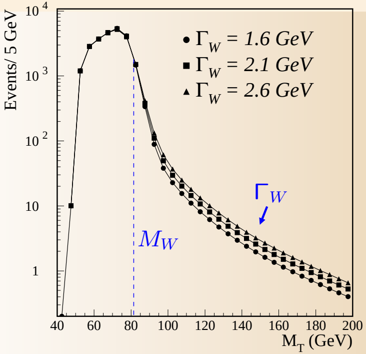
A similar Jacobian peak is present in $d\sigma/dp_T^\nu$

More on lepton transverse mass

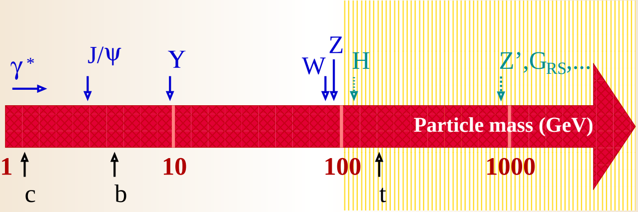
Exercise

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 commonly used to measure M_W. Γ_W is found from $d\sigma/dM_T^{e\nu}$ at large $M_T^{e\nu}$

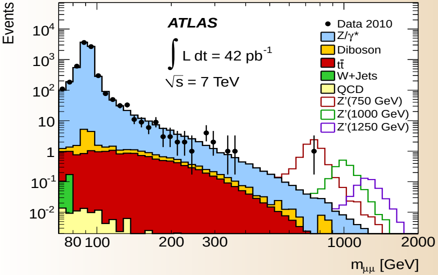


Final states in DY-like processes

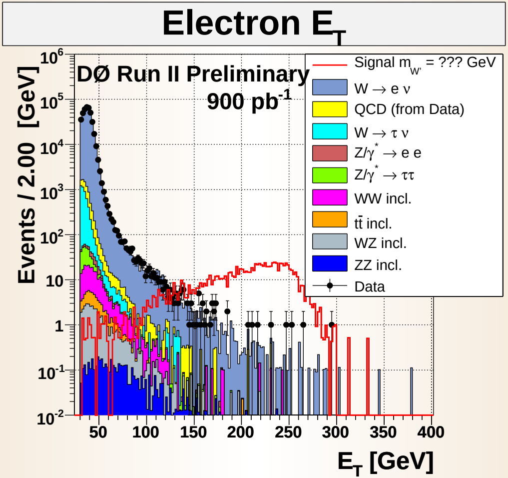


New physics at $Q > 100$ GeV

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

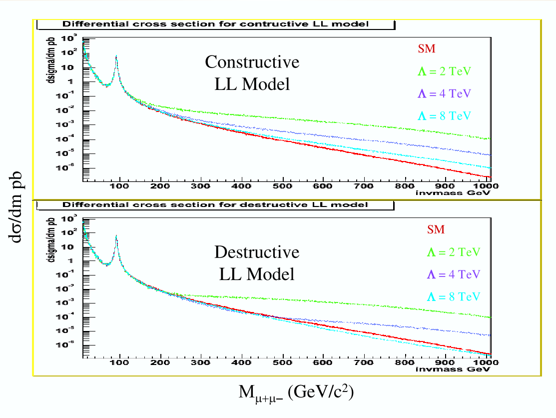


Search for heavy states at DO



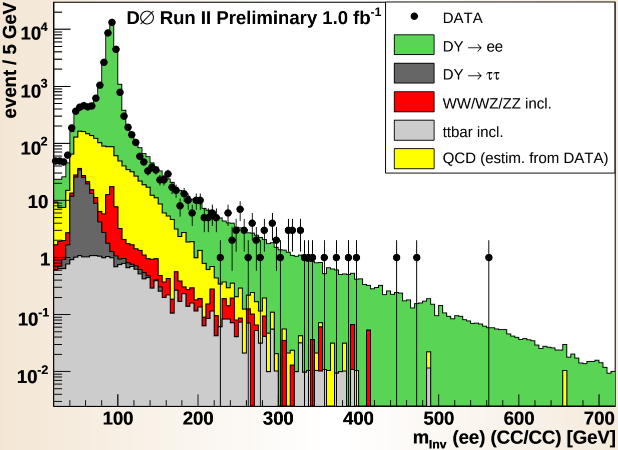
$W' \to \ell\nu$

Search for heavy states at DO



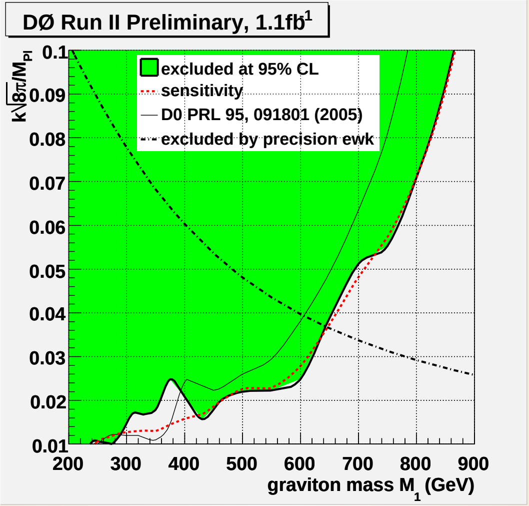
Leptoquark $\rightarrow \mu\mu$

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 $\to ee, \gamma\gamma$

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 (NNLO,...)
- 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
- Various resummations (Q_T, small x, threshold, heavy-quark....)
- Drell-Yan production in heavy-ion scattering