Theory at LHC

Sven-Olaf Moch

Sven-Olaf.Moch@desy.de

DESY, Zeuthen

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Theory at LHC

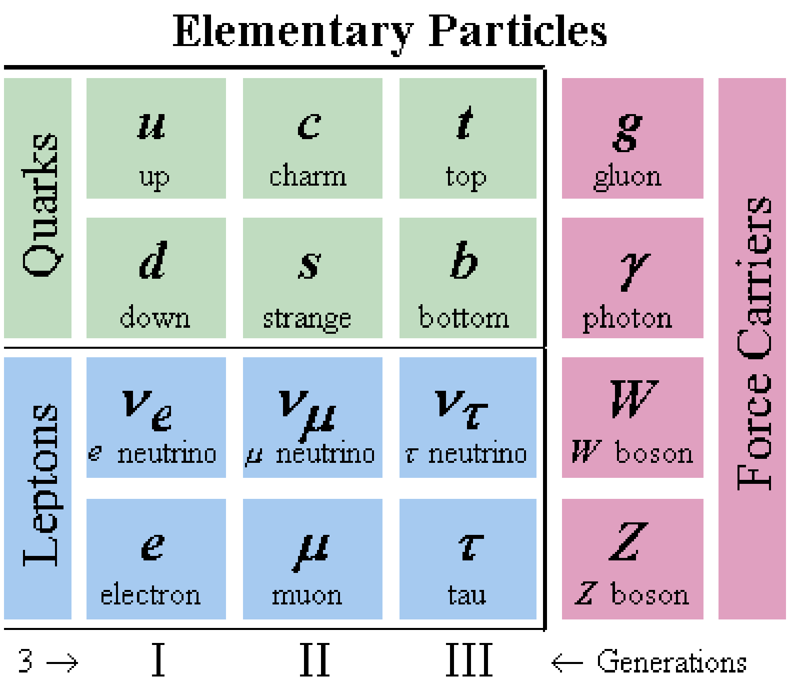
- Introduction to QCD and Electroweak Physics *Monday, August 03, 2009*
- Higgs Physics, Supersymmetry and beyond *Tuesday, August 04, 2009*

Lecture 1

- The big questions
- Basics of perturbative QCD
- QCD factorization for hard scattering
- Parton luminosity
- Jet cross sections at hadron colliders
- $W^{\pm}$ and Z-boson production at LHC
- Hadro-production of Top-Quarks

Things we do know

- Elementary particles
  - fermions (leptons, quarks)
    (constituents of matter)
  - bosons
    (carrier particles of forces)



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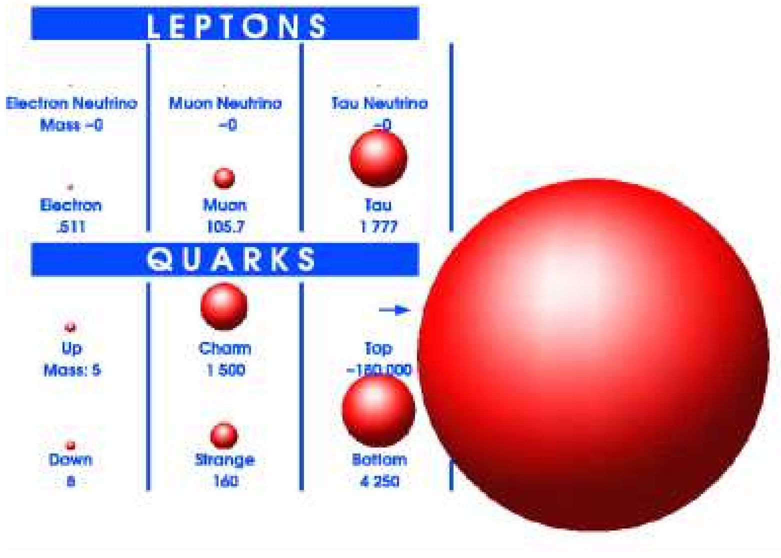
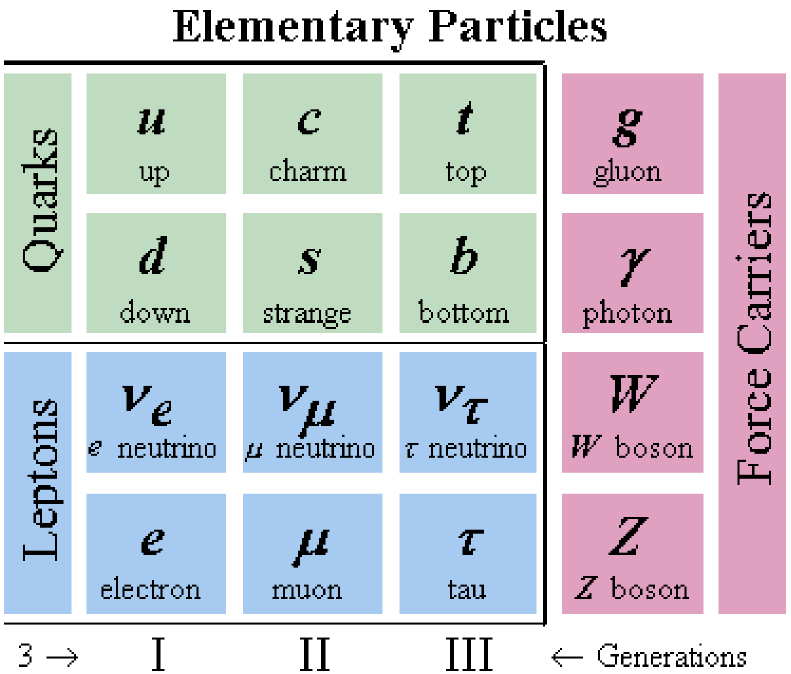
  - fermions (leptons, quarks) (constituents of matter)
  - bosons (carrier particles of forces)
- Masses of fermions





massive neutrinos first glimpse beyond SM

The Nobel Prize in Physics 2008

"for the discovery of the mechanism of spontaneous broken symmetry in subatomic physics"

"for the discovery of the origin of the broken symmetry which predicts the existence of at least three families of quarks in nature"


Photo: SCANPIX

Yoichiro Nambu

1/2 of the prize

USA

Enrico Fermi Institute,
University of Chicago
Chicago, IL, USA

b. 1921


Photo: Kyodo/Reuters

Makoto Kobayashi

1/4 of the prize

Japan

High Energy Accel…
Resear…


Photo: Kyoto University

Toshihide Maskawa

1/4 of the prize

Japan

b. 1940

Nobel prize 2008 for spontaneous symmetry breaking and CP violation

Titles, data and places gi… …ove refer to the time of the award.

Things we want to know

The Big Questions

- What is the origin of mass?
- What is 96% of
  the universe made of?
- Why is there no more
  antimatter?
- Do extra dimensions
  of space really exist?
- . . .

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Frankfurter Allge
ZEITUNG FÜR DEUTSCHLAND
Verschwinden wir im ... en Loch?

FAZ on Sep 10, 2008

BSM theory landscape (Murayama)

Highest energies at colliders until 201x

Energy frontier

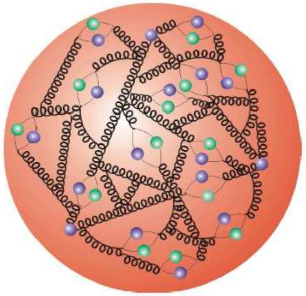
- Search for Higgs boson, new massive particles at highest energies

$$\mathrm{E} = \mathrm{m\,c}^2$$

Hadron colliders

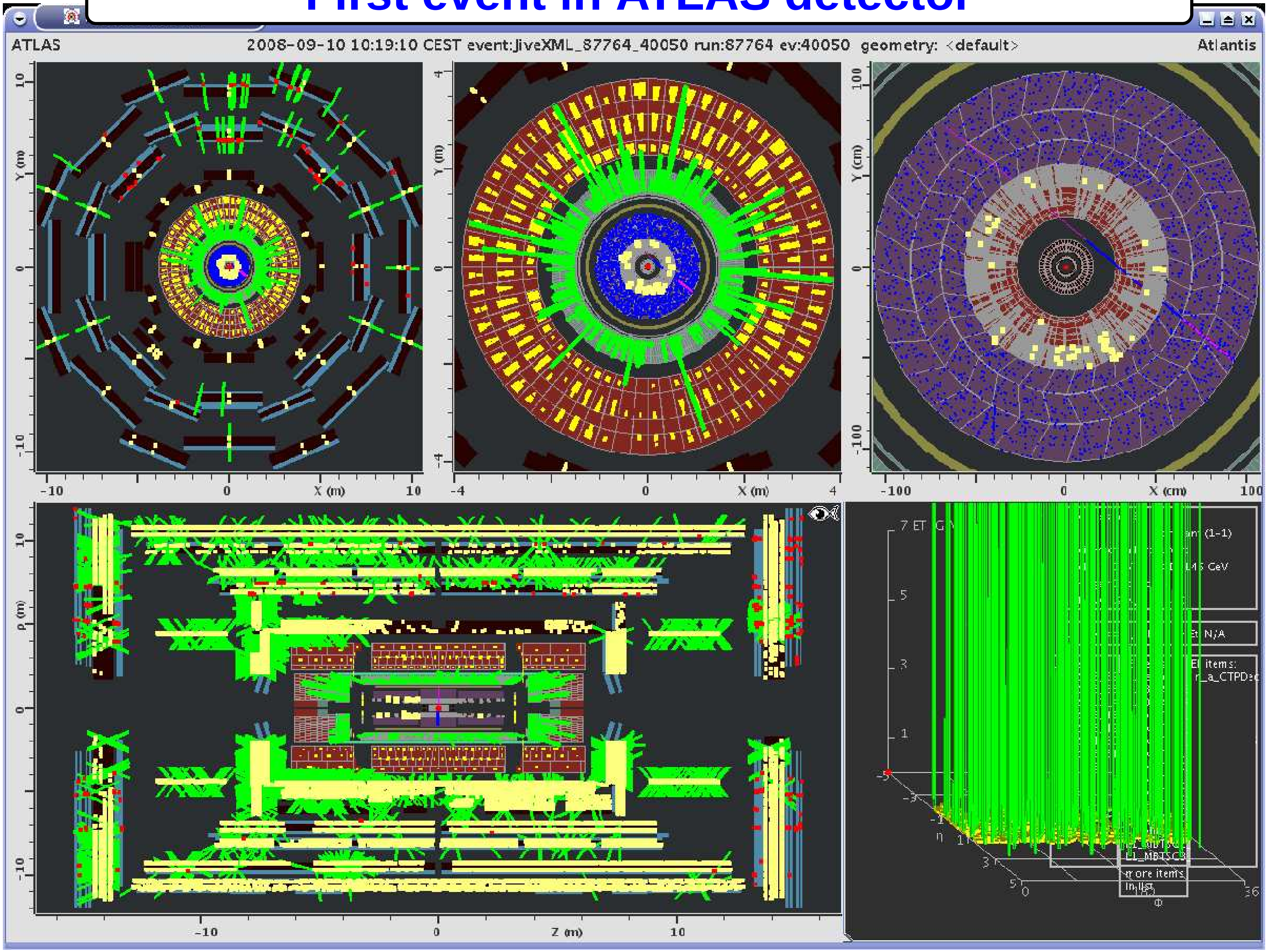
- Proton–(anti)-proton collisions reach TeV-scale
  - Tevatron $\sqrt{S} = 1.96$TeV (until 2009), LHC with $\sqrt{S} = 14$TeV

- Proton: composite multi-particle bound state
  - collider: "wide-band beams" of quarks and gluons
- Protons are heavy
  - no significant synchrotron radiation $\sim \left(\frac{E}{m}\right)^4 / r$



Large Hadron Collider

First event in ATLAS detector



Theoretical predictions for the LHC

Challenge

- Solve master equation

$$\text{new physics} = \text{data} - \text{Standard Model}$$

- New physics searches require understanding of SM background
- LHC explores the energy frontier
  - theory has to match or exceed accuracy of LHC data

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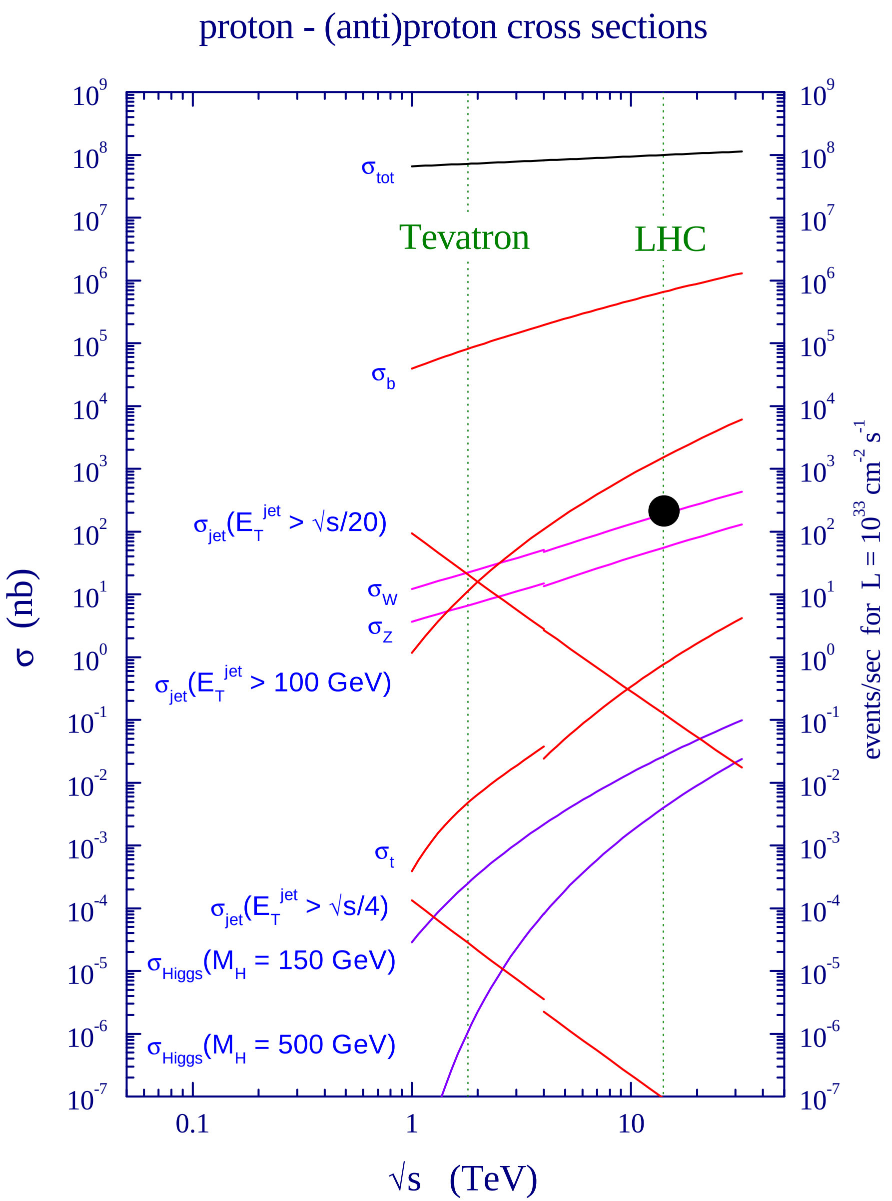
Tools

- LHC is a QCD machine
  - perturbative QCD is essential and established part of toolkit (we no longer “test” QCD)
- Electroweak corrections important for precision predictions

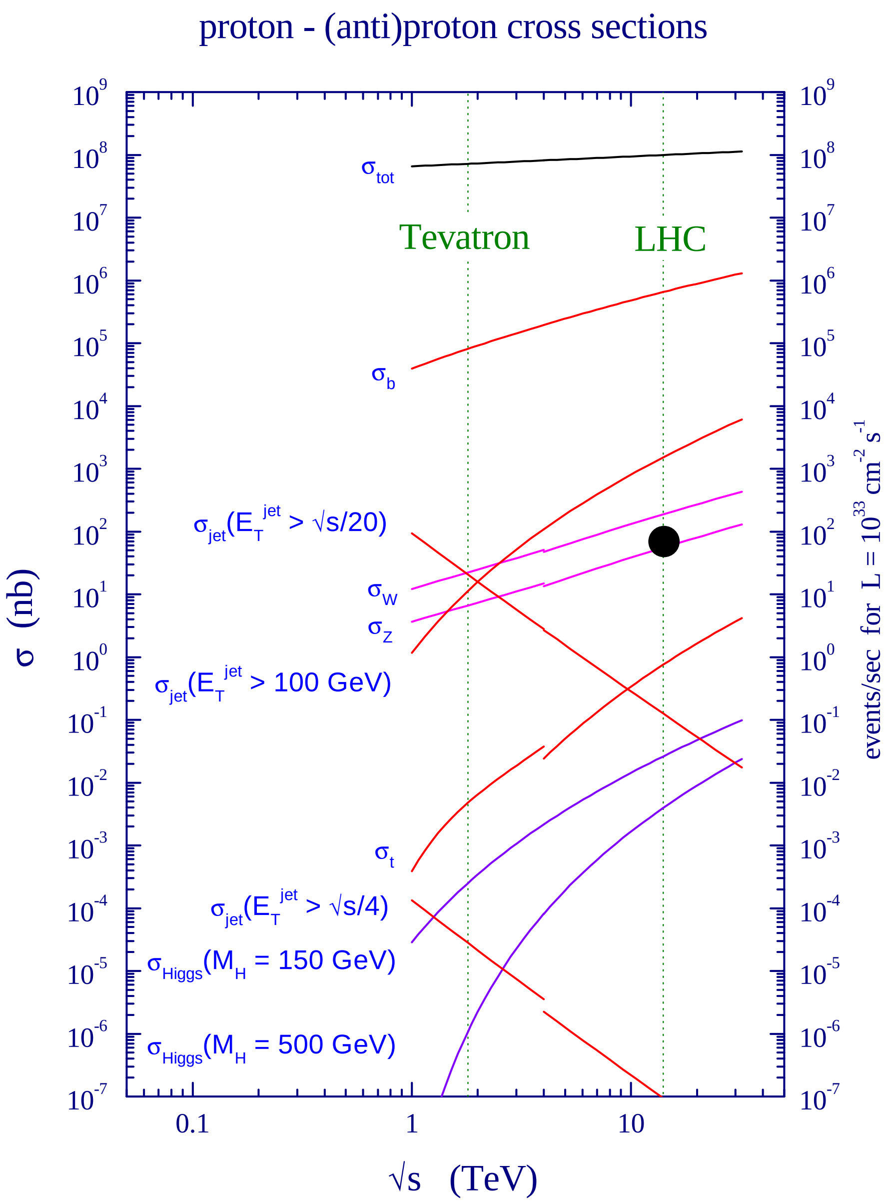
Proton-proton scattering

- Large rates expected for many Standard Model processes
- $\sigma_W \sim 150$ nb
  - B$R(W \to e + \mu) \sim 20\%$
    10 fb^{-1} gives 300M leptonic events
    rate(10^{33} cm^{-2} s^{-1}) $\sim$ 30 Hz
    rate(10^{34} cm^{-2} s^{-1}) $\sim$ 300 Hz



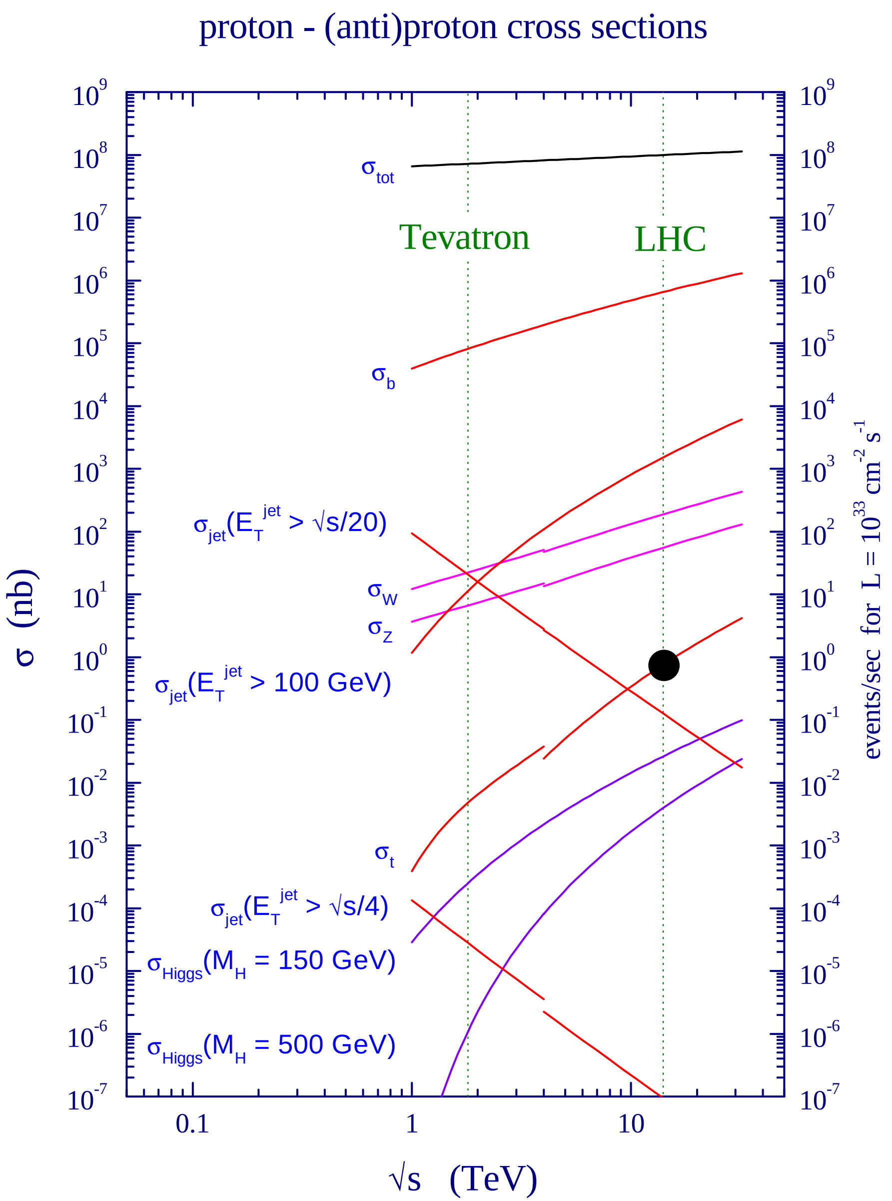
Proton-proton scattering

- Large rates expected for many Standard Model processes
- $\sigma_Z \sim 50$ nb
  - B$R(W \to ee + \mu\mu) \sim 6.6\%$
    10 fb^{-1} gives 33M leptonic events
    rate(10^{33} cm^{-2} s^{-1}) $\sim$ 3.5 Hz
    rate(10^{34} cm^{-2} s^{-1}) $\sim$ 35 Hz



Proton-proton scattering

- Large rates expected for many Standard Model processes
- $\sigma_{t\bar{t}} \sim 800$ pb
  - B$R(W \to e + \mu) \sim 30\%$
    10 fb^{-1} gives 2.4M leptonic events
    rate(10^{33} cm^{-2} s^{-1}) $\sim$ 0.2 Hz
    rate(10^{34} cm^{-2} s^{-1}) $\sim$ 2 Hz



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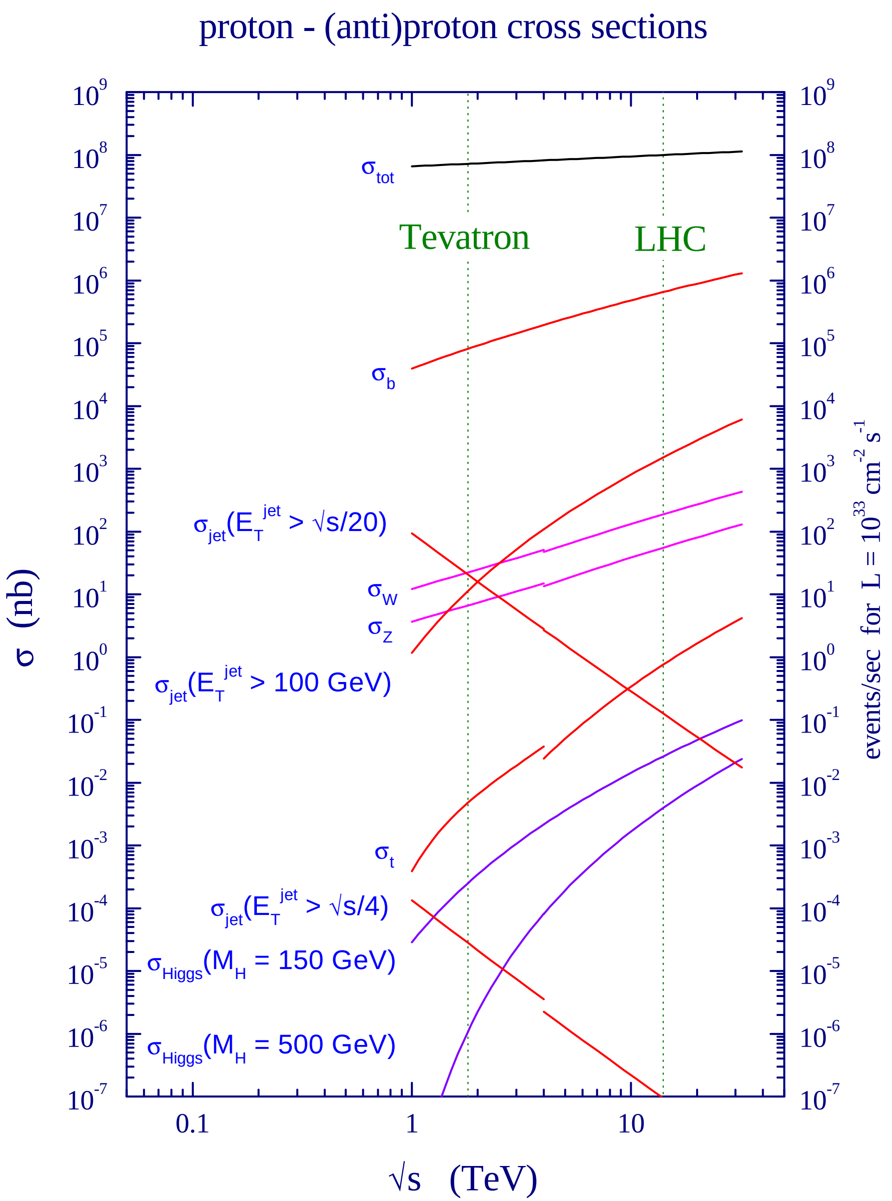
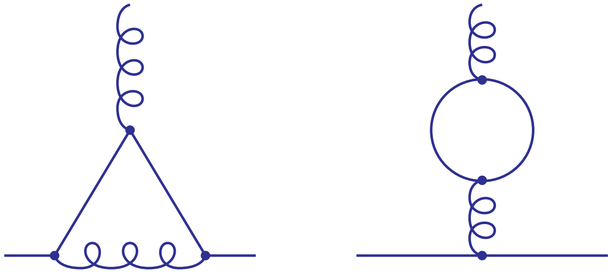
- New physics signals
  - cross section predictions
    $\sigma_{\text{new physics}} \sim \mathcal{O}(1-10)$ pb
  - superpartners in MSSM (neutralinos, charginos, squarks, gluinos, ...), KK modes
  - searches often assume 100 fb^{-1}

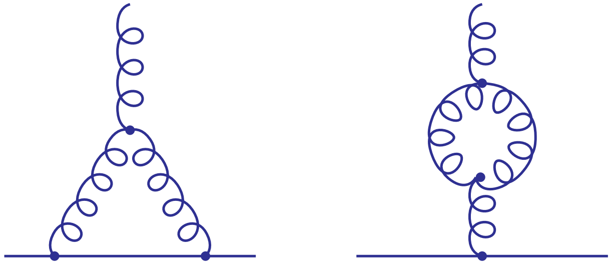


Asymptotic freedom in QCD

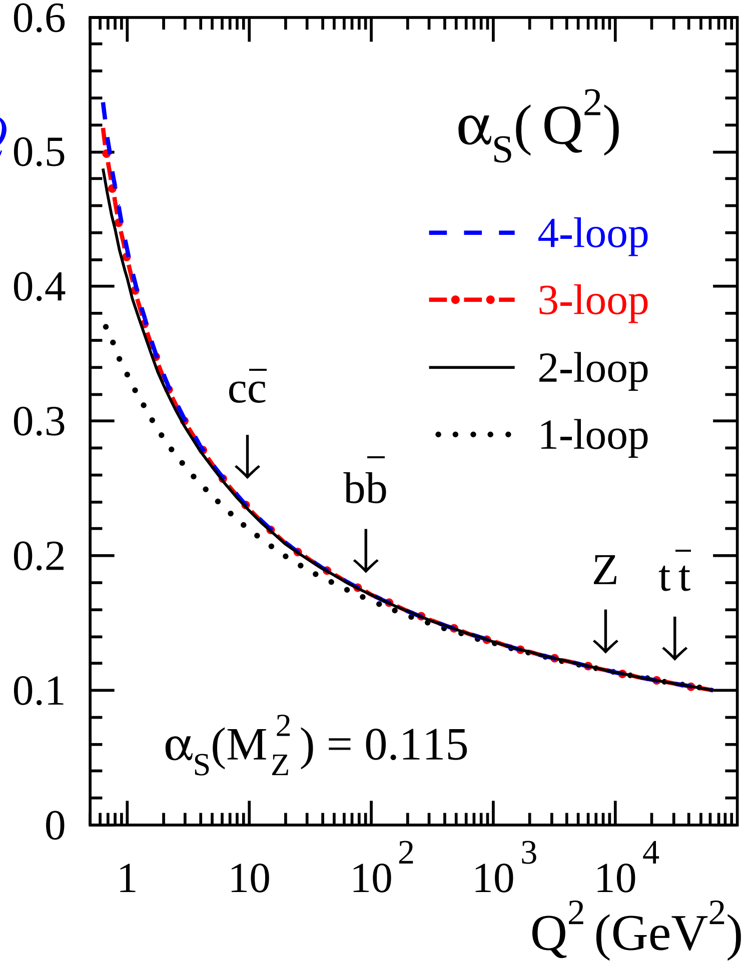
- Effective couplung constant α_s
  depends on resolution, momentum scale Q



  – screening (like in QED)



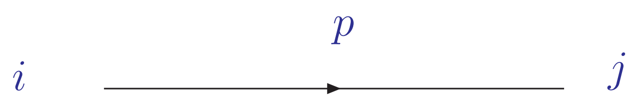
  – anti-screening (color charge of g)



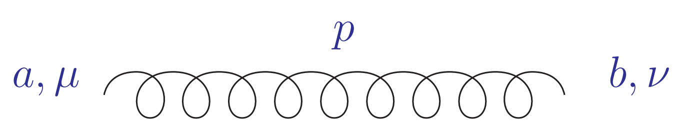
- At large scales: application of perturbation theory (but $\alpha_s \gg \alpha_{\mathrm{QED}}$)

Feynman rules

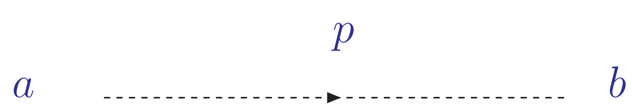
- Propagators
  - fermions, gluons, ghosts
  - covariant gauge



$$\delta^{ij} \, \frac{\mathrm{i}}{\not{p} - m}$$



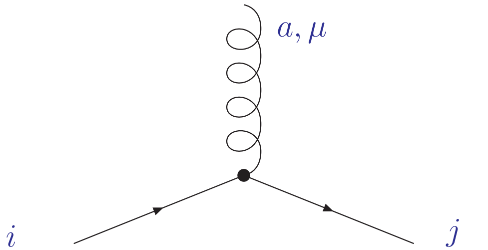
$$\delta^{ab} \, \mathrm{i} \left(\frac{-g^{\mu\nu}}{p^2} + (1-\lambda) \frac{p^\mu p^\nu}{(p^2)^2} \right)$$



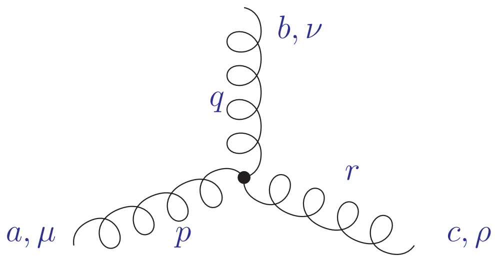
$$\delta^{ab} \, \frac{\mathrm{i}}{p^2}$$

Feynman rules (cont'd)

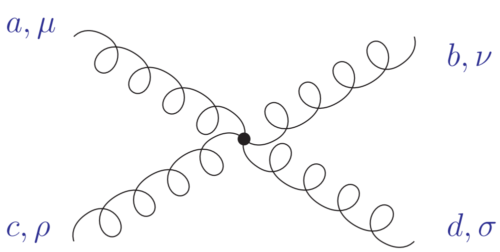
- Vertices



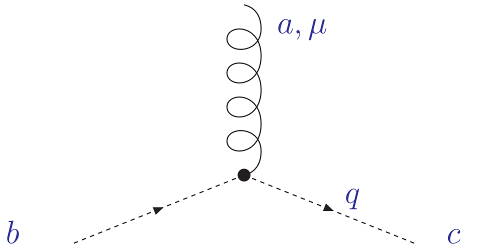
$$-\mathrm{i}\, g \, (t^a)_{ji} \, \gamma^\mu$$



$$-g \, f^{abc} \, \left((p-q)^\rho g^{\mu\nu} + (q-r)^\mu g^{\nu\rho} + (r-p)^\nu g^{\mu\rho}\right)$$



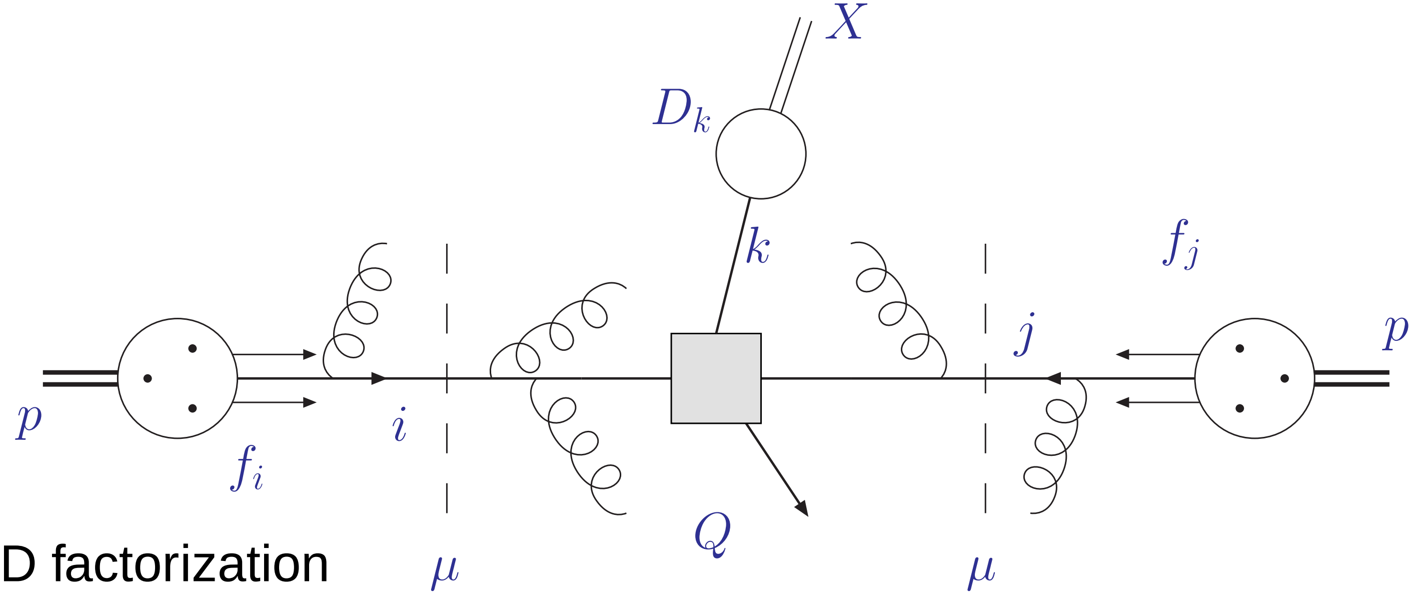
$$-\mathrm{i}\, g^2 \, f^{xac} f^{xbd} \, (g^{\mu\nu} g^{\rho\sigma} - g^{\mu\sigma} g^{\nu\rho})$$
$$-\mathrm{i}\, g^2 \, f^{xad} f^{xbc} \, (g^{\mu\nu} g^{\rho\sigma} - g^{\mu\rho} g^{\nu\sigma})$$
$$-\mathrm{i}\, g^2 \, f^{xab} f^{xcd} \, (g^{\mu\rho} g^{\nu\sigma} - g^{\mu\sigma} g^{\nu\rho})$$



$$g \, f^{abc} \, q^\mu$$

Perturbative QCD at colliders

- Hard hadron-hadron scattering
  - constituent partons from each incoming hadron interact at short



- QCD factorization
  - separate sensitivity to dynamics from different scales

$$\sigma_{pp \to X} = \sum_{ijk} f_i(\mu^2) \otimes f_j(\mu^2) \otimes \hat{\sigma}_{ij \to k}\left(\alpha_s(\mu^2), Q^2, \mu^2\right) \otimes D_{k \to X}(\mu^2)$$

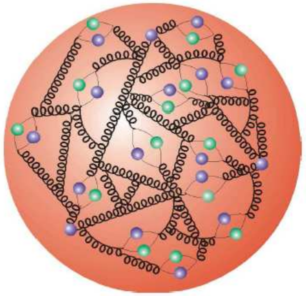
  - factorization scale μ, subprocess cross section $\hat{\sigma}_{ij \to k}$ for parton types i, j and hadronic final state X

Hard scattering cross section

- Standard approach to uncertainties in theoretical predictions
  - variation of factorization scale μ: $\frac{d}{d\ln\mu^2}\sigma_{pp\to X} = \mathcal{O}(\alpha_s^{l+1})$

$$\sigma_{pp\to X} = \sum_{ijk} f_i(\mu^2) \otimes f_j(\mu^2) \otimes \hat{\sigma}_{ij\to k}\left(\alpha_s(\mu^2), Q^2, \mu^2\right) \otimes D_{k\to X}(\mu^2)$$

- Parton cross section $\hat{\sigma}_{ij\to k}$ calculable pertubatively in powers of α_s
  - constituent partons from incoming protons interact at short distances of order $\mathcal{O}(1/Q)$
- Parton luminosity $f_i \otimes f_j$
  - proton: very complicated multi-particle bound state
  - colliders: wide-band beams of quarks and gluons



- Final state X: hadrons, mesons, jets, . . .
  - fragmentation function $D_{k\to X}(\mu^2)$ or jet algorithm
  - interface with showering algorithms (Monte Carlo)

Approaches to the calculation of σ_{had}

- LO (leading order)
  - Automated tree level calculations in Standard Model, MSSM, . . .
    (Madgraph, Sherpa, Alpgen, CompHEP, . . .)
  - LO + parton shower
  - String inspired techniques
- NLO (next-to-leading order)
  - Analytical (or numerical) calculations of diagrams yield parton level Monte Carlos (NLOJET++, MCFM, . . .)
  - NLO + parton shower (MC@NLO, VINCIA)
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  - selected results known (mostly inclusive kinematics)
- N^3LO (next-to-next-to-next-to-leading order)
  - very few . . .

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$\leftarrow$ level of talk here

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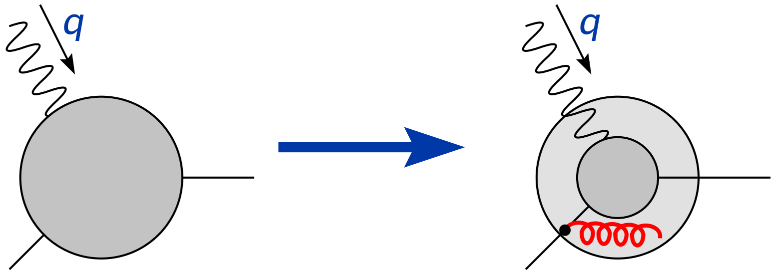
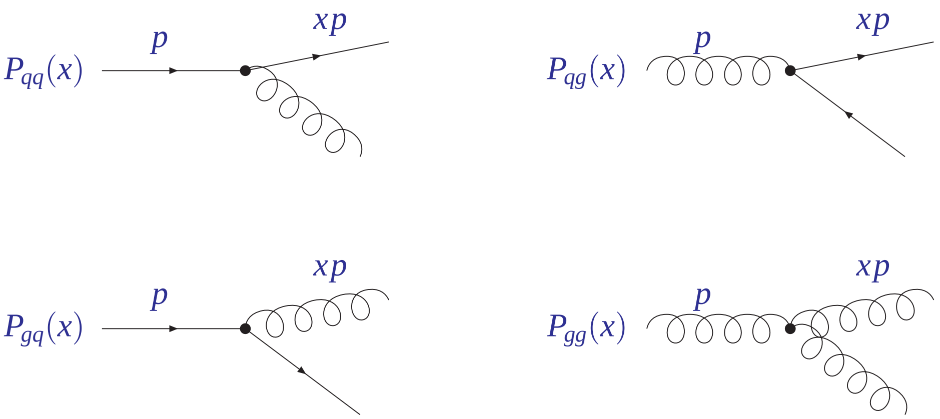
difficult

Parton luminosity



- Proton in resolution $1/Q \longrightarrow$ sensitive to lower momentum partons

- Feynman diagrams in leading order



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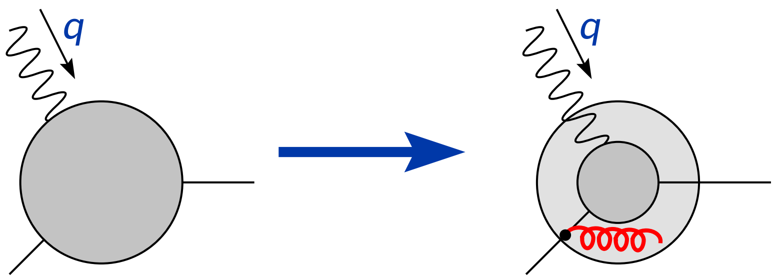

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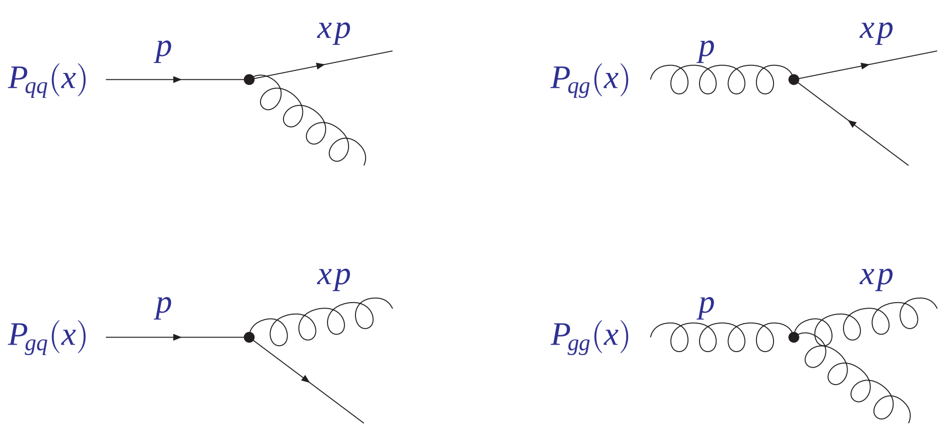


- Proton in resolution $1/Q \longrightarrow$ sensitive to lower momentum partons

- Evolution equations for parton distributions f_i
  - predictions from fits to reference processes (universality)

$$\frac{d}{d \ln \mu^2} f_i(x, \mu^2) = \sum_k \left[P_{ik}(\alpha_s(\mu^2)) \otimes f_k(\mu^2) \right] (x)$$

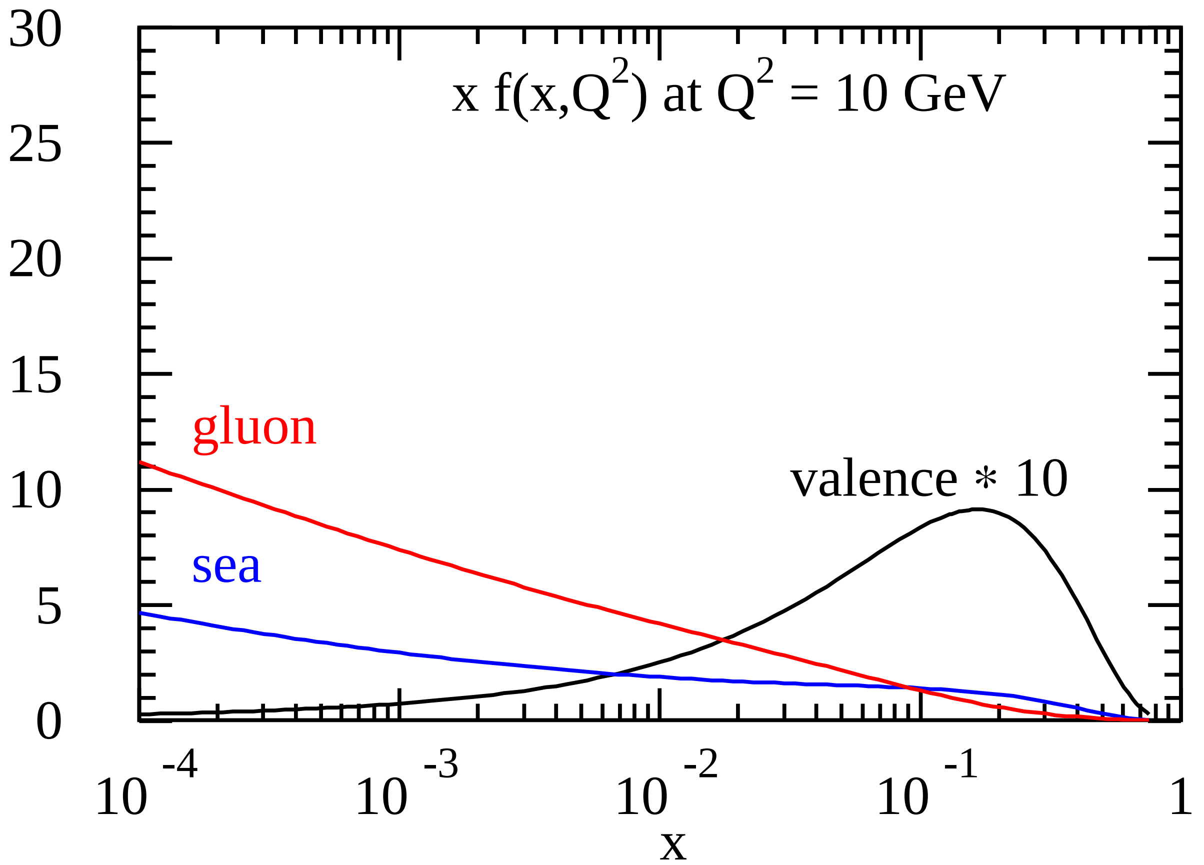
- Splitting functions P

$$P = \underbrace{\alpha_s P^{(0)} + \alpha_s^2 P^{(1)}} + \alpha_s^3 P^{(2)} + \ldots$$

NLO: standard approximation (large uncertainties)

Parton distributions in proton

- Valence $q - \bar{q}$ (additive quantum numbers) sea (part with $q + \bar{q}$)



- Parameterization (bulk of data from deep-inelastic scattering)
  - structure function $F_2 \longrightarrow$ quark distribution
  - scale evolution (perturbative QCD) $\longrightarrow$ gluon distribution

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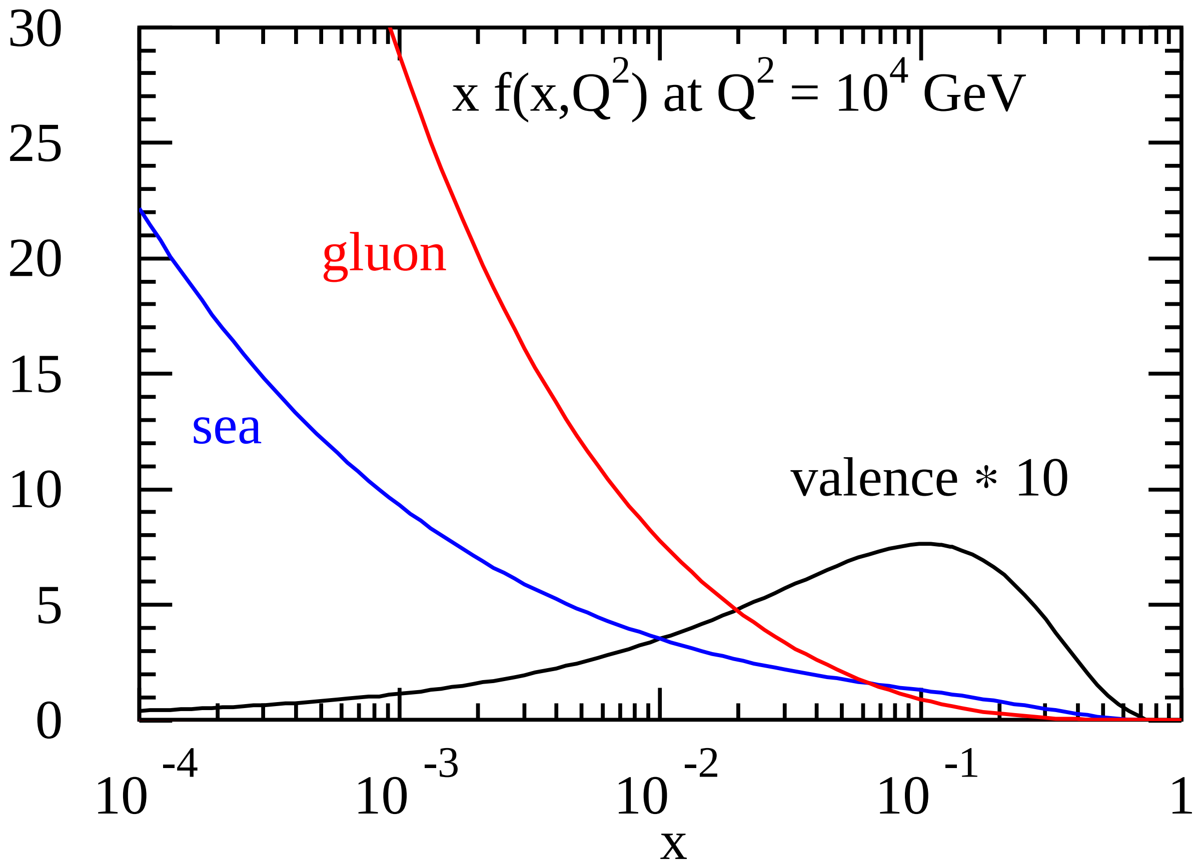

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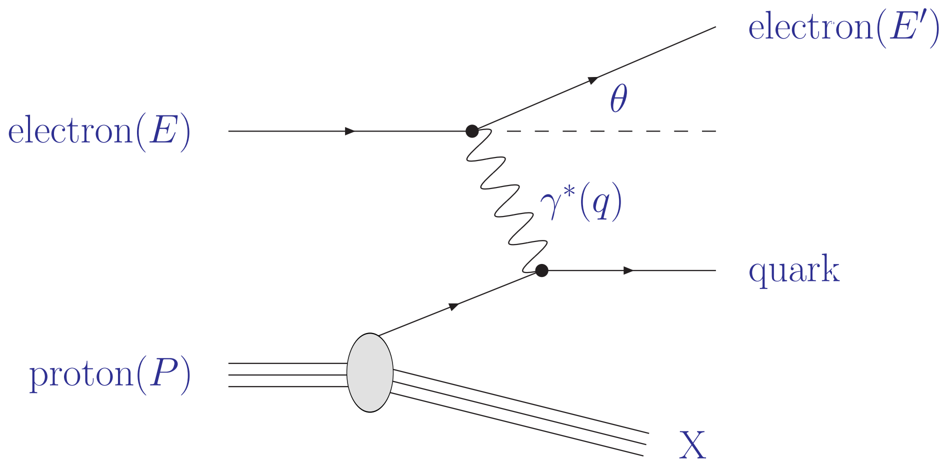
Inelastic electron-proton scattering



- Virtuality of photon: resolution

$$Q^2 \equiv -q^2 = 4EE' \sin^2(\theta/2)$$

- Bjorken variable: inelasticity

$$x = \frac{Q^2}{2P \cdot q} < 1$$

- Cross section (X inclusive): proton structure function F_i^p

$$(E - E') \frac{d\sigma}{d\Omega \, dE'} \stackrel{\text{lab}}{=} \underbrace{\frac{\alpha^2 \cos^2 \frac{\theta}{2}}{4E^2 \sin^4 \frac{\theta}{2}}}_{\text{Mott-scattering (point-like)}} \left\{ F_2^p(x, Q^2) + \tan^2 \frac{\theta}{2} \, F_1^p(x, Q^2) \right\}$$

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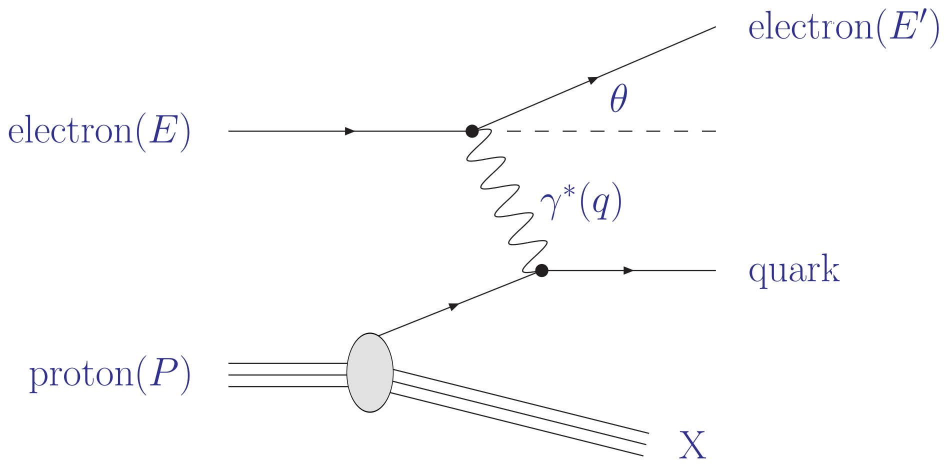

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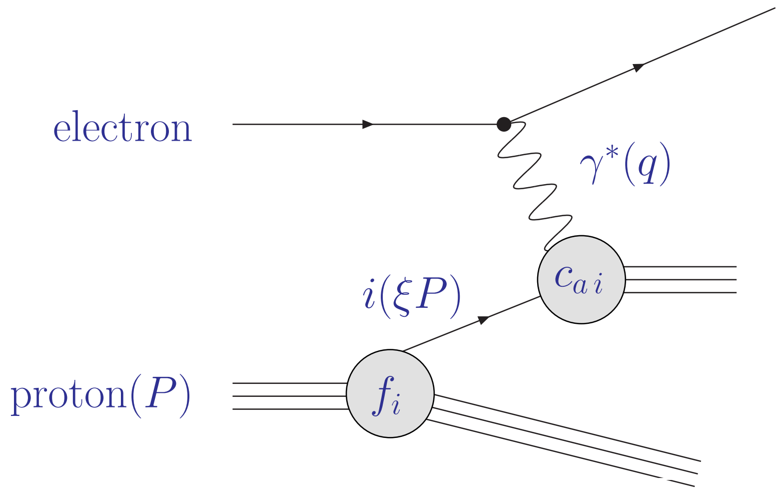
- Deep-inelastic scattering (Bjorken limit: $Q^2 \to \infty$ and x fixed)
  Parton modell (quasi-free point-like constituents, incoherence)
  $$F_2(x,Q^2) \simeq F_2(x) = \sum_i e_i^2\, x f_i(x)$$
  - $x f_i(x)$ distribution for momentum fraction x of parton i

QCD corrections in deep-inelastic scattering



- Structure function F_2 (up to terms $\mathcal{O}(1/Q^2)$)
  - Renormalization/factorization scale $\mu = \mathcal{O}(Q)$

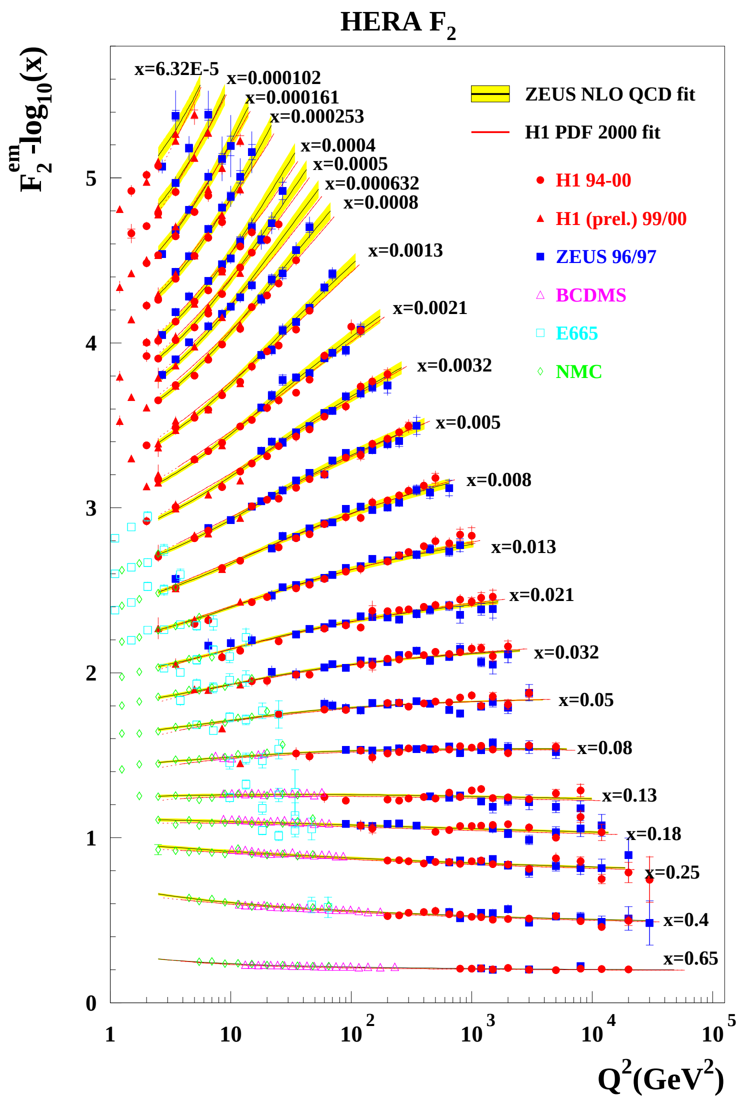
$$x^{-1} F_2^p(x, Q^2) \;=\; \sum_i \int_x^1 \frac{d\xi}{\xi}\, c_{2,i}\left(\frac{x}{\xi}, \alpha_s(\mu^2), \frac{\mu^2}{Q^2}\right) f_i^p(\xi, \mu^2)$$

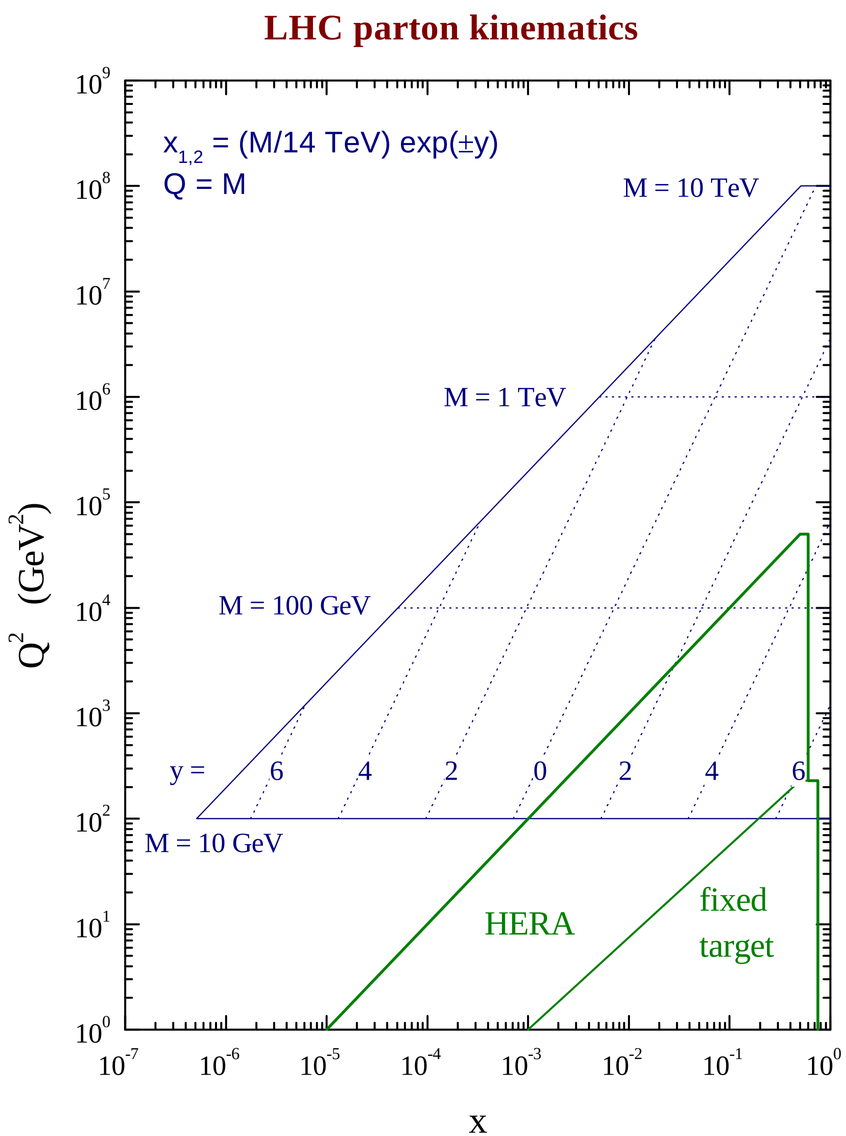
- Coefficient functions c_a

$$c_a \;=\; \underbrace{\alpha_s^{n_a}\left[c_a^{(0)} + \alpha_s\, c_a^{(1)}\right.}\; + \; \alpha_s^2\, c_a^{(2)} \; + \; \ldots \left.\right]$$

NLO: standard approximation (large uncertainties)

PDFs from HERA to LHC

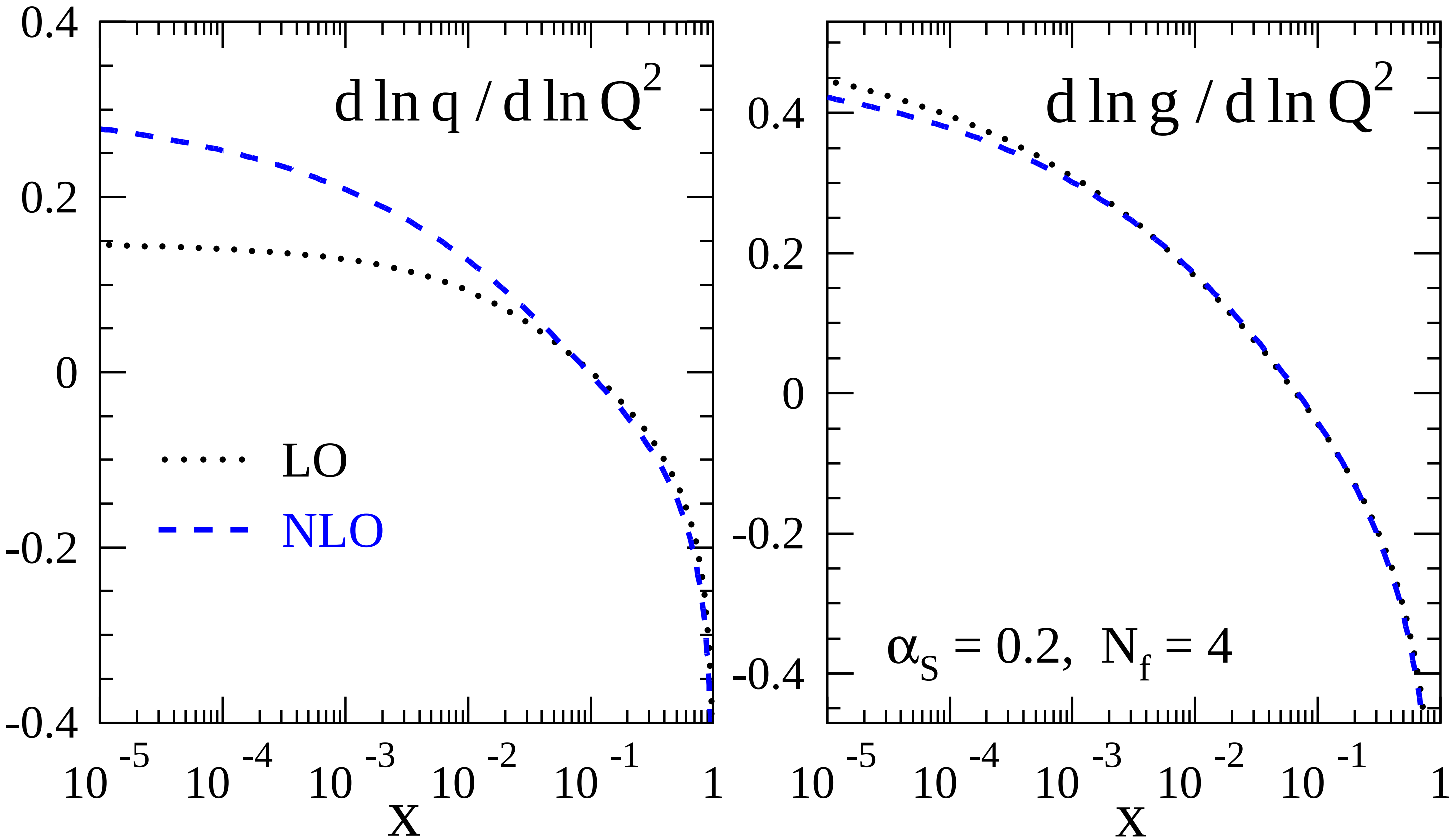




- Precision HERA data on F_2
- Scale evolution of PDFs in Q over two to three orders

Perturbative stability of evolution

- Scale derivatives of quark and gluon distributions at $Q^2 \approx 30$ GeV^2



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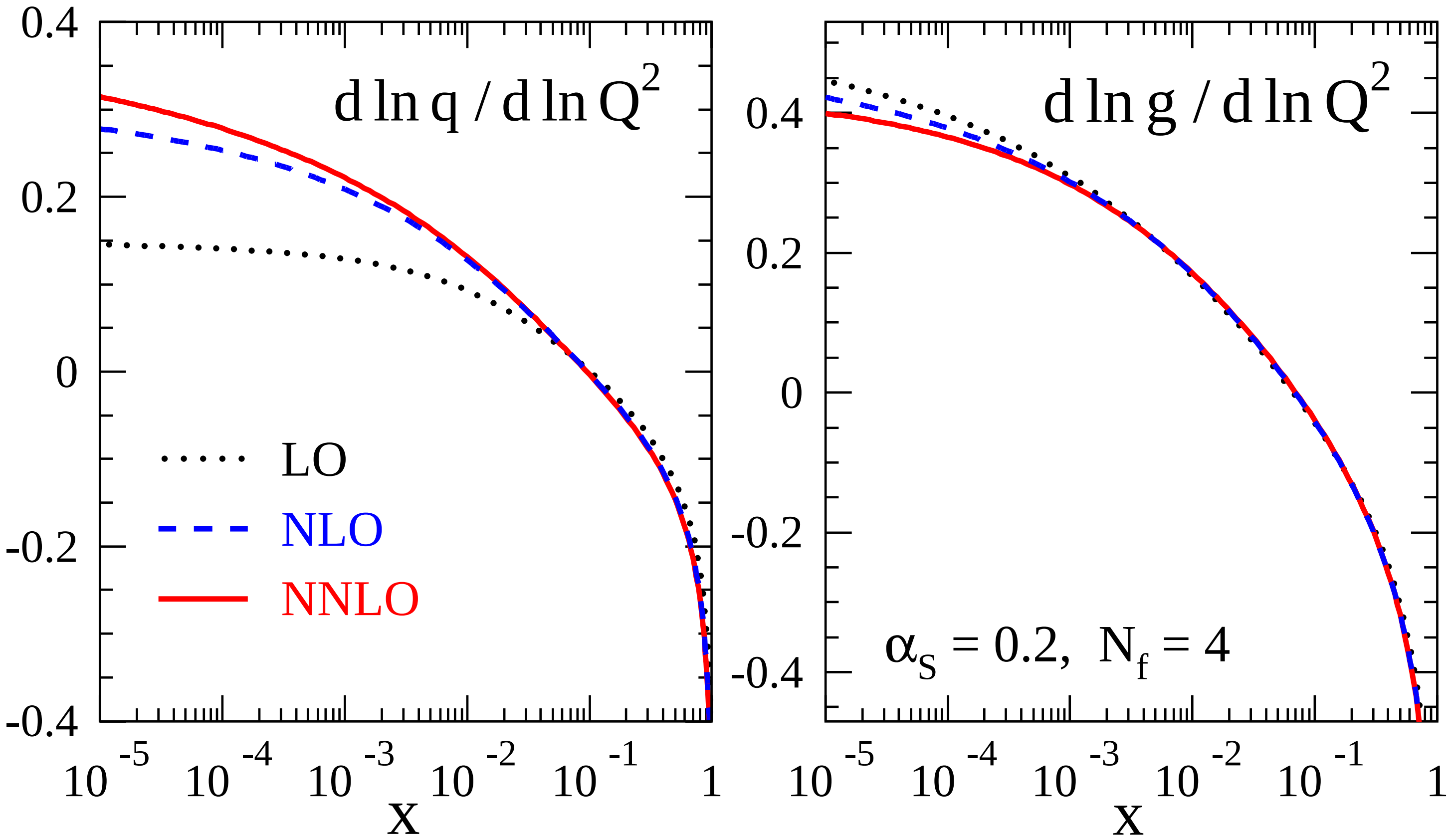


- Expansion very stable except for very small momenta $x \lesssim 10^{-4}$

Parton cross sections

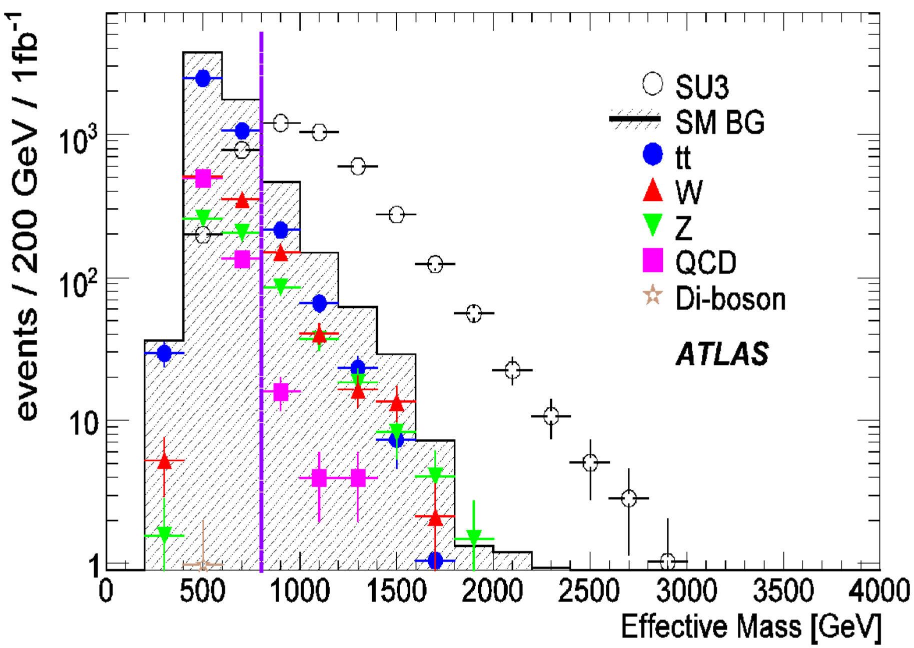
How precise are the predictions?

- Isolation of new physics signal from background
  - look for deviations from the Standard Model
    (if possible data driven)
  - e.g. R-parity conserved SUSY with cascade decays into LSP
    multiple jets, leptons and missing E_T

Perturbative QCD

- NLO QCD corrections are essential NLO (important for rates)
  - large K-factors, new parton channels may dominate beyond tree level
  - e.g. $pp \to Z(\to \nu\bar{\nu}) + 4$jets is $\mathcal{O}(\alpha_s^4)$ and $\Delta(\alpha_s^{\rm LO}) \simeq 10\%$ gives
    $\Delta(\sigma^{\rm LO}) \simeq 40\%$

SUSY searches



- Typical selection cuts
  - Njet ≥ 4
  - $E_{T(1)} > 100$GeV
  - $E_{T(2,3,4)} > 50$GeV
  - $M_{\text{eff}} = \text{MET} + \sum_i E_{Ti}$
- Example: mSUGRA, point SU3
  - $m_0 = 100$ GeV, $m_{1/2} = 300$ GeV, $\tan\ \beta = 6, A_0 = -300, \mu > 0$

- Discrimination of BSM signal from background requires precise predictions (exact LO matrix elements)
- SM background in high-end tail of missing E_T
  e.g. $pp \to Z(\to \nu\bar{\nu}) + 4$jets
- Significance of potential disagreement between data and MadGraph/Sherpa/Algen/... ?

LHC “priority” wishlist

process ($V \in \{\gamma, W^\pm, Z\}$)	background to	accomplished
$pp \to VV + 1$ jet	$t\bar{t}H$, new physics	$WW + 1$ jet
$pp \to H + 2$ jets	H production by vector boson fusion (VBF)	$H + 2$ jets
$pp \to t\bar{t}b\bar{b}$	$t\bar{t}H$	$t\bar{t}b\bar{b}$
$pp \to t\bar{t} + 2$ jets	$t\bar{t}H$	
$pp \to VVb\bar{b}$	VBF $\to VV$, $t\bar{t}H$, new physics	
$pp \to VV + 2$ jets	VBF $\to VV$	
$pp \to V + 3$ jets	various new physics signatures	$W + 3$ jets
$pp \to VVV$	SUSY trilepton	ZZZ, WWZ

Les Houches 2005 [hep-ph/0604120]

Why are one-loop corrections difficult ?

- Outline of a generic NLO calculation

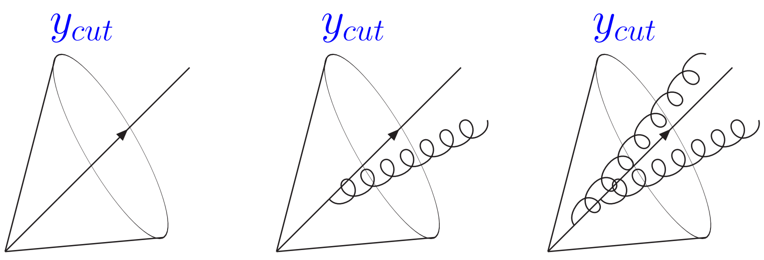
Real corrections	Virtual corrections
- subtractions (IR-divergent)	+ subtractions (IR-divergent)

Cancellation of singularities
Finite partonic cross sections
Phase space integration
Convolution with PDFs
Monte Carlo

- All conceptual issues solved (“just” technical work)
- However, no general libraries available
- **Speed and stability** are the important criteria in practice

Jet definitions

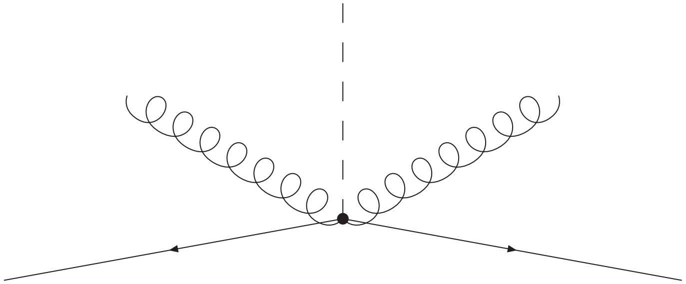
- Historically: Sterman-Weinberg criterium for two-jet event
  - energy fraction $1 - \epsilon$ in cone of half angle δ
  - not practical for multi-particle events
- Modern modelling of jets
  - cone- or k_t-algorithms



- JADE algorithm

$$\min\,(p_i + p_j)^2 = \min 2E_iE_j\,(1 - \cos\theta_{ij}) > y_{\rm cut}\,s$$

  - combines also soft gluons at large relative k_t (disadvantage)
    e.g. potential three-jet event



Jets in hadronic collisions

- Cone algorithm
  - define cone of radius R in η, ϕ for $R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$

(Some) uses of hadronic di-jets

- Hadronic di-jets: large statistics even with high-p_t cuts
  - experimental calibration (HCAL uniformity, establish missing E_t)
  - gluon jets constrain gluon PDF at medium/large x
  - searches for quark sub-structure (di-jet angular correlations)

Kinematics (differential)

- Proton-proton scattering (two broad-band beams of incoming partons)
  - cms of parton-parton scattering boosted wrt incoming protons
- Final state variables (simple transformations under longitud. boosts)

$$p^\mu = (E, p_x, p_y, p_z) = (m_t \cosh\, y, p_t \sin\, \phi, p_t \cos\, \phi, m_t \sinh\, y)$$

  - rapidity $y = \frac{1}{2} \ln \left(\frac{E + p_z}{E - p_z} \right)$
  - transverse momentum p_t and mass $m_t = \sqrt{p_t^2 + m^2}$
  - azimuthal angle ϕ

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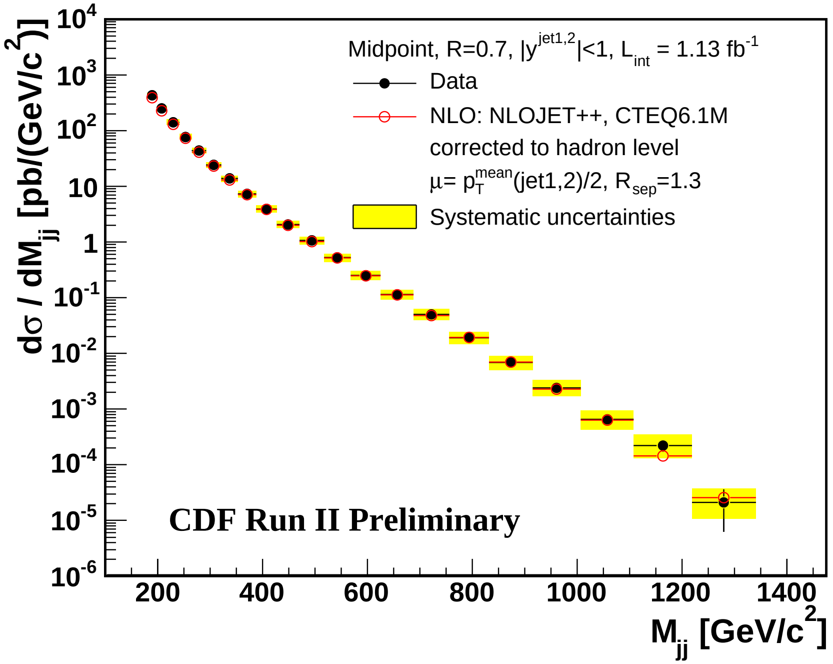
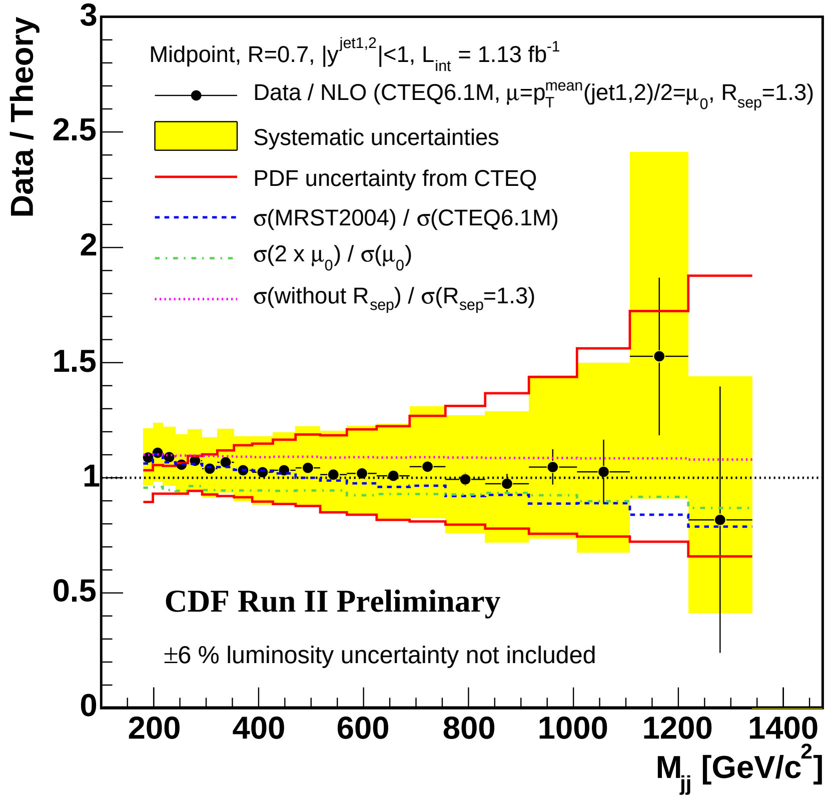
  - transverse momentum p_t and mass $m_t = \sqrt{p_t^2 + m^2}$
  - azimuthal angle ϕ
- Differences in rapidity Δy and azimuthal angle $\Delta\phi$ invariant under boosts
- In practice (for $E \gg m_p$)
  - pseudo-rapidity $\eta = -\ln \tan \left(\frac{\theta}{2} \right)$ with angle from beam axis

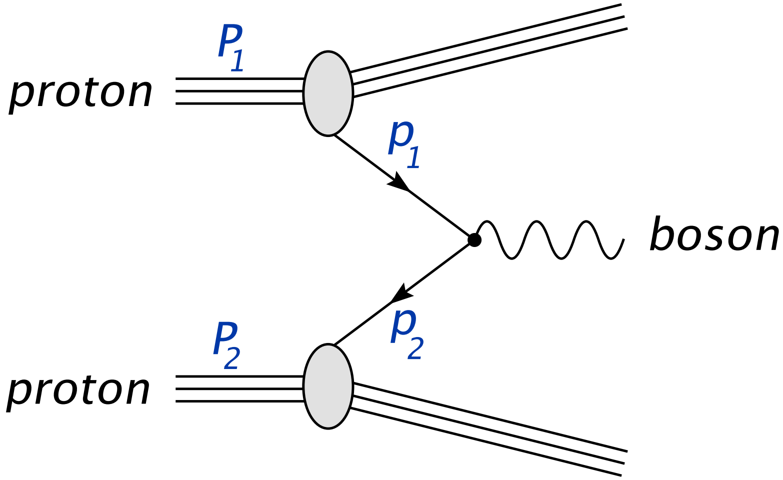
Jets at Tevatron





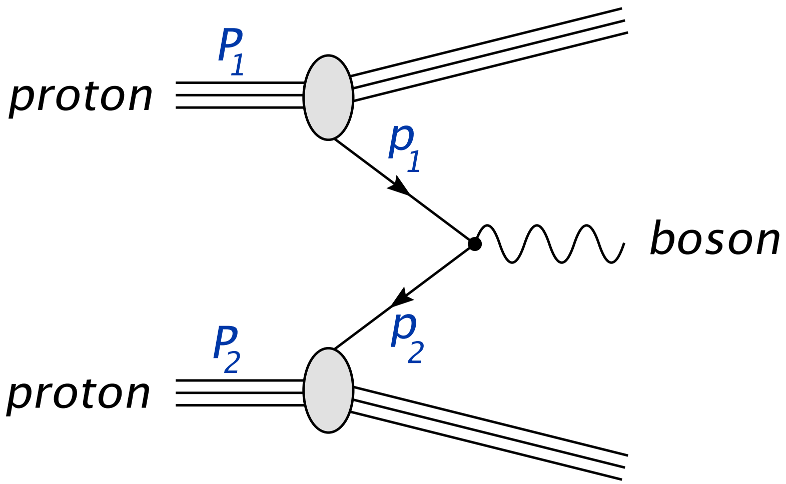
- Di-jet invariant mass distribution
  - agreement with perturbative QCD over eight orders of magnitude
  - larger uncertainites for high M_{jj}^2

Vector boson production



- Kinematical variables (inclusive)
  - energy (cms) $s = Q^2$ (space-like)
  - scaling variable $x = M^2_{W^\pm/Z}/s$

Vector boson production



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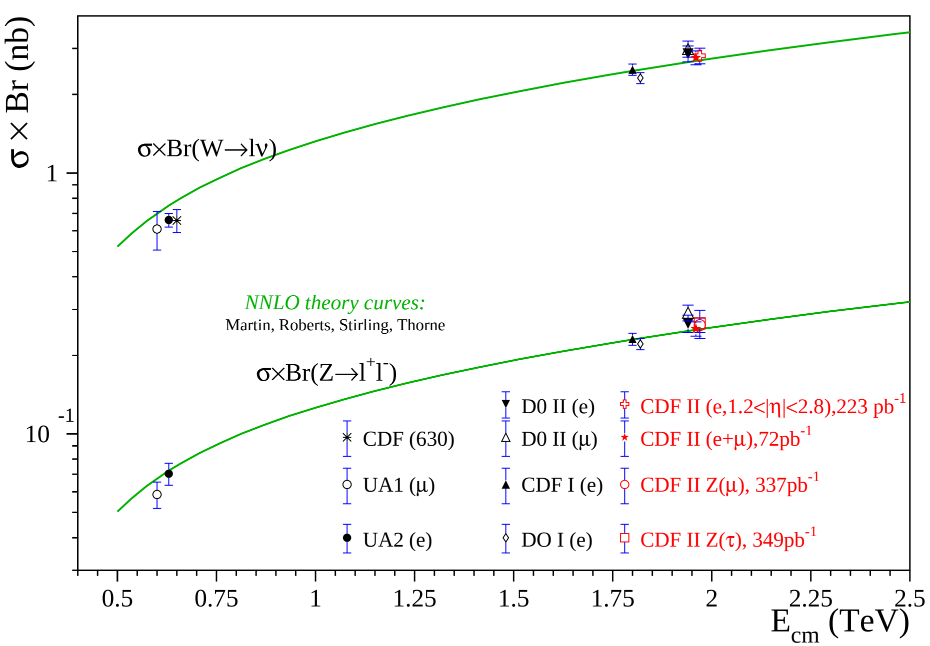
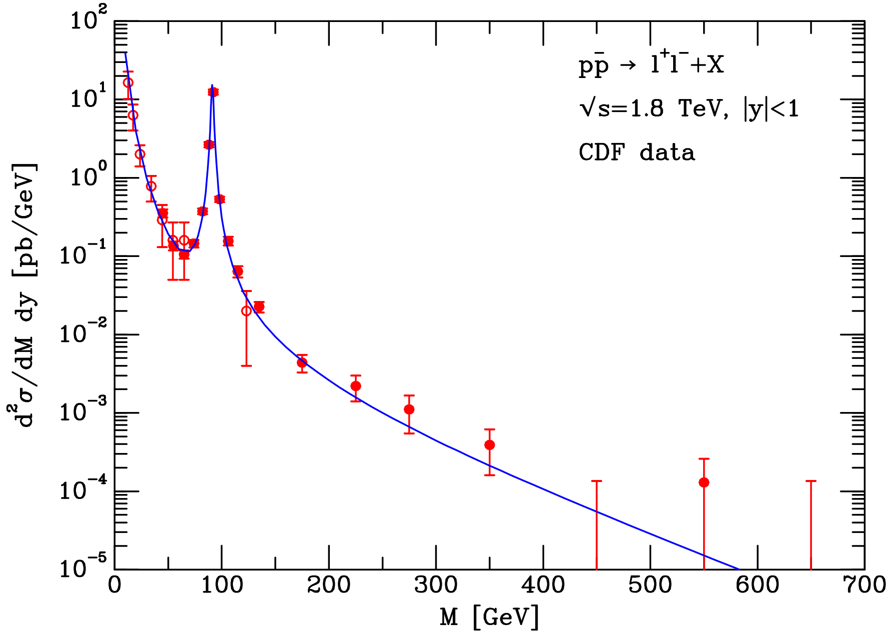


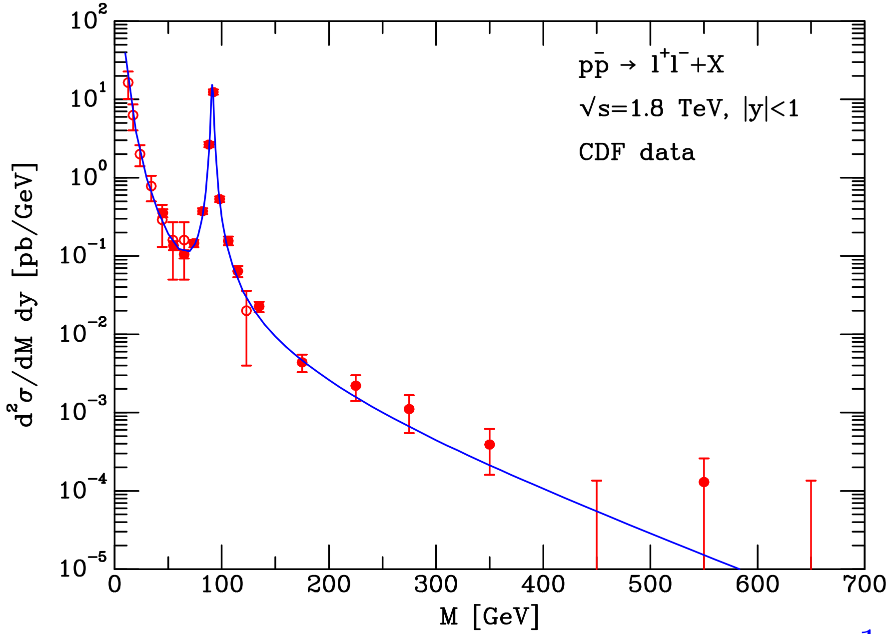
- 20 years of measurements of $W^\pm$ and Z cross sections at hadron colliders

Differential distributions



- Invariant mass distribution $\frac{d\sigma}{dM^2}$ of lepton pair for Z-production in $p\bar{p}$-collisions
  - CDF data at $\sqrt{s} = 1.8$ TeV and NLO QCD prediction

Differential distributions



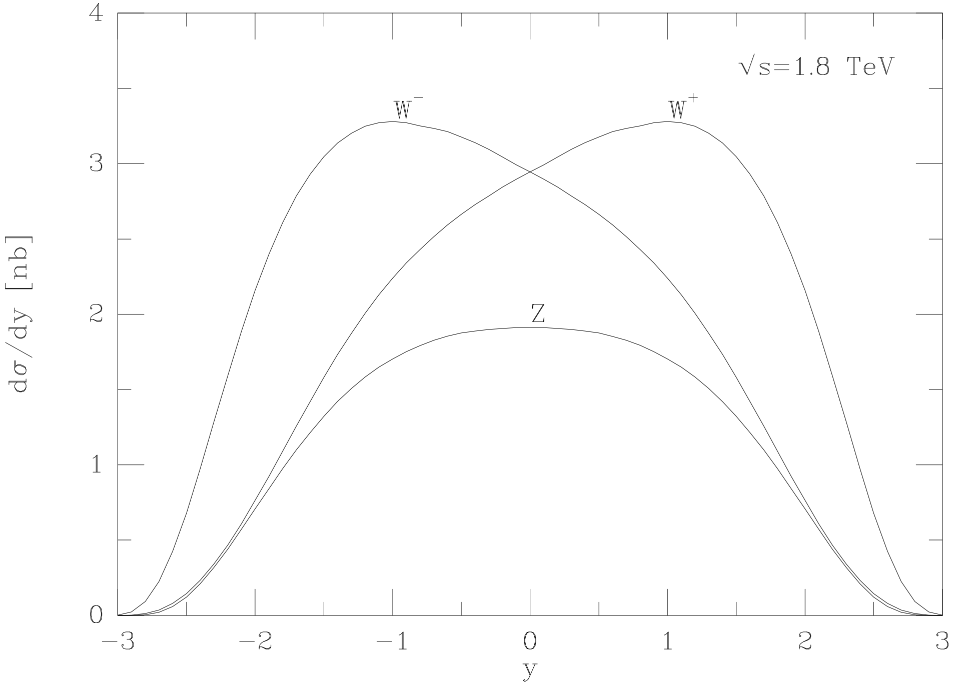
- Invariant mass distribution $\frac{d\sigma}{dM^2}$ of lepton pair for Z-production in $p\bar{p}$-collisions
  - CDF data at $\sqrt{s} = 1.8$ TeV and NLO QCD prediction

$$M^4 \frac{d\sigma}{dM^2} = \sigma^{(0)} \frac{1}{N} \frac{M^2}{s} \int_0^1 dx_1\, dx_2\, \delta\left(x_1 x_2 - \frac{M^2}{s}\right)$$

$$\times \sum_q e_q^2 \left\{ f_q(x_1)\, f_{\bar{q}}(x_2) + f_{\bar{q}}(x_1)\, f_q(x_2) \right\}$$

- Double-differential cross section $\frac{d\sigma}{dM^2 dy}$ local in PDFs
  - $y = \frac{1}{2} \ln\left(\frac{x_1}{x_2}\right)$ lepton-pair rapidity

$W^{\pm}$ asymmetry

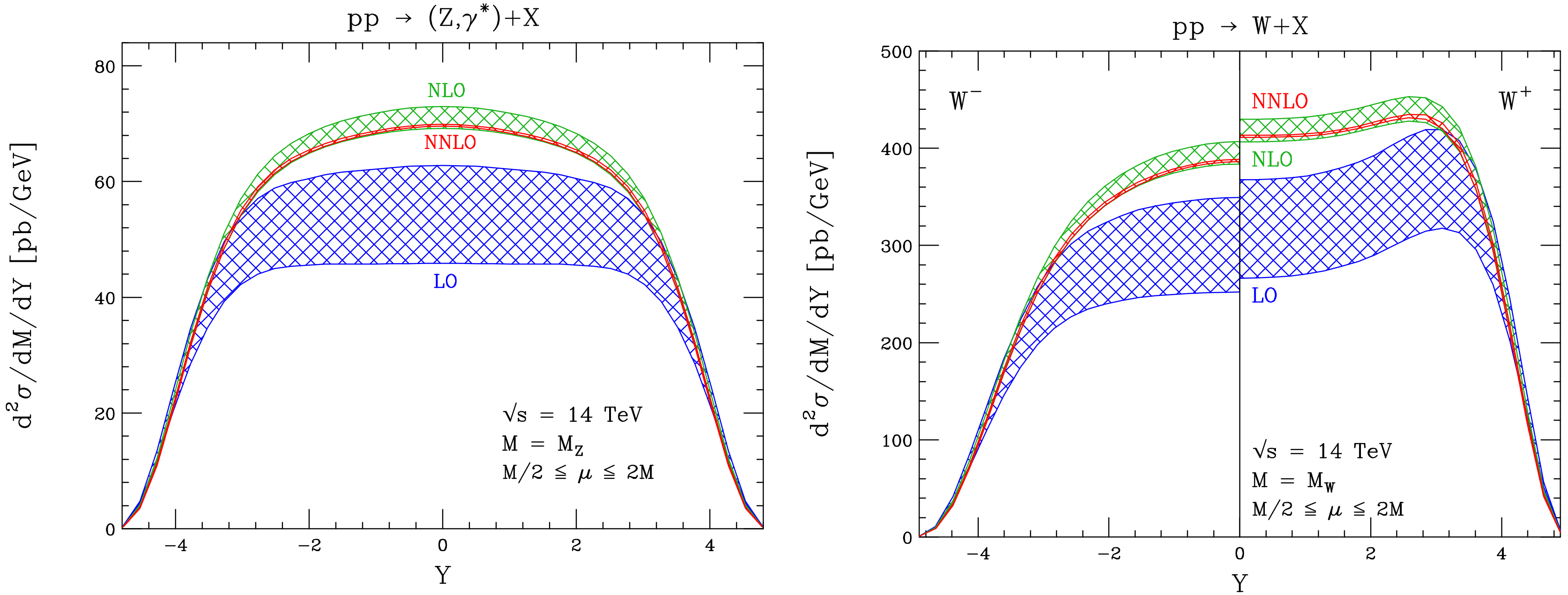


- Rapidity distributions for $W^{\pm}$- and Z-production in $p\bar{p}$-collisions
- CP invariance $\longrightarrow$ $\frac{d\sigma}{dy}$ for Z-production symmetric around $y = 0$

- $W^{\pm}$ rapidity asymmetry sensitive to flavor decomposition of proton

$$A_W(y) = \frac{d\sigma(W^+)/dy - d\sigma(W^-)/dy}{d\sigma(W^+)/dy + d\sigma(W^-)/dy} \simeq \frac{u(x_1)d(x_2) - d(x_1)u(x_2)}{u(x_1)d(x_2) + d(x_1)u(x_2)}$$

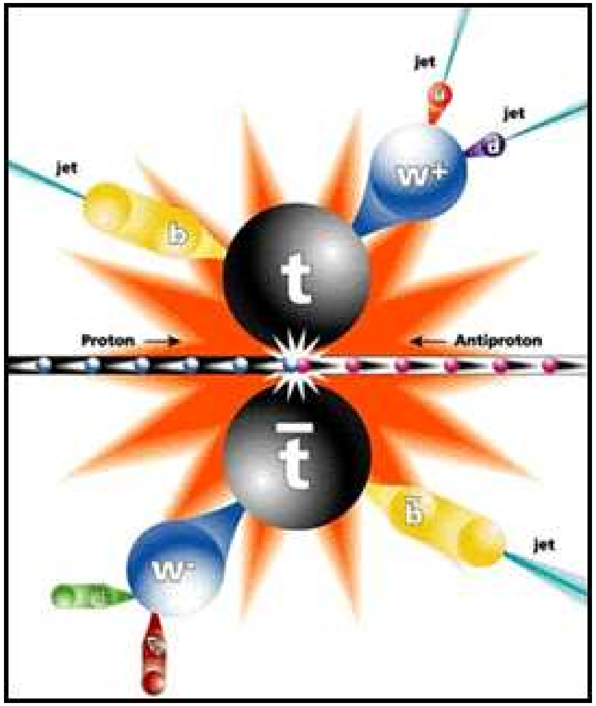
Differential distributions at NNLO in QCD



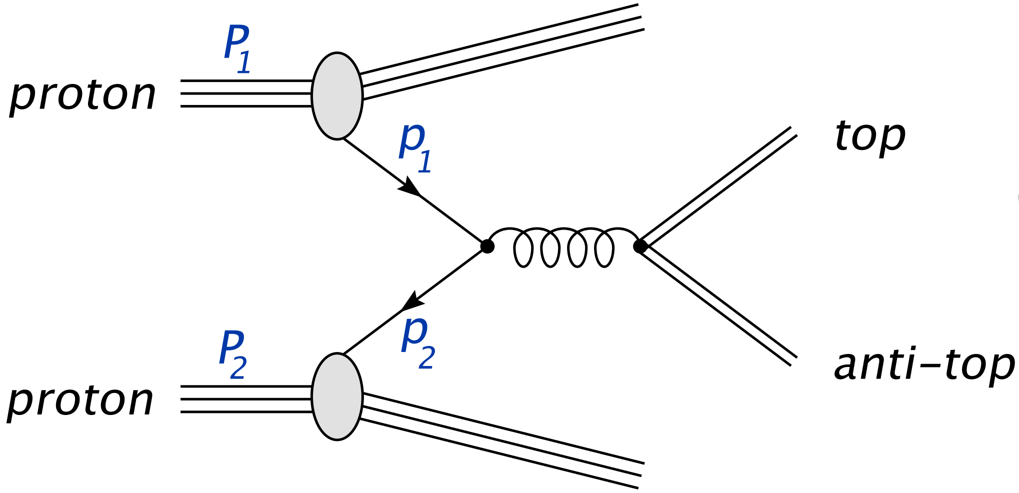
- $W^{\pm}, Z$-boson rapidity distribution with scale variation $m_{W,Z}/2 \leq \mu \leq 2m_{W,Z}$
  Anastasiou, Petriello, Melnikov '05
- Reduction of theoretical uncertainties (renormalization / factorization scale) to level of 1% in NNLO QCD analysis
  Dissertori '05

Hadronic top-quark pair-production

- Tevatron: $t\bar{t}$-pair with subsequent decay
  - $t \rightarrow Wb$ decay and leptonic or hadronic $W^{\pm}$-decay



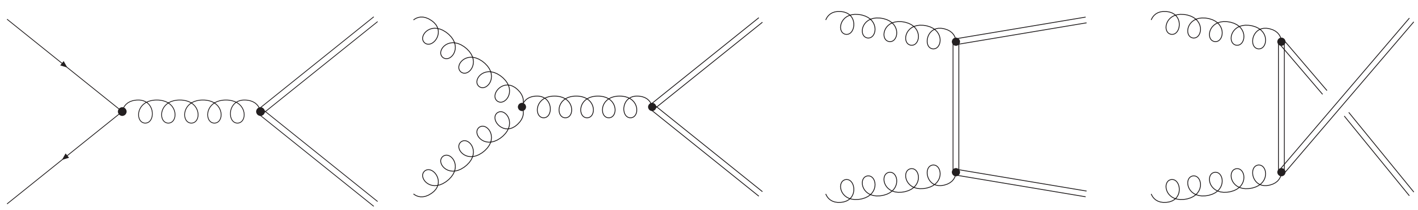
Top-quark pair-production



- Top decay
  leptonic: $t \to W^+ + b \to l^+ + \nu + b$
  hadronic: $t \to W^+ + b \to q + \bar{q} + b$

- Leading order Feynman diagrams

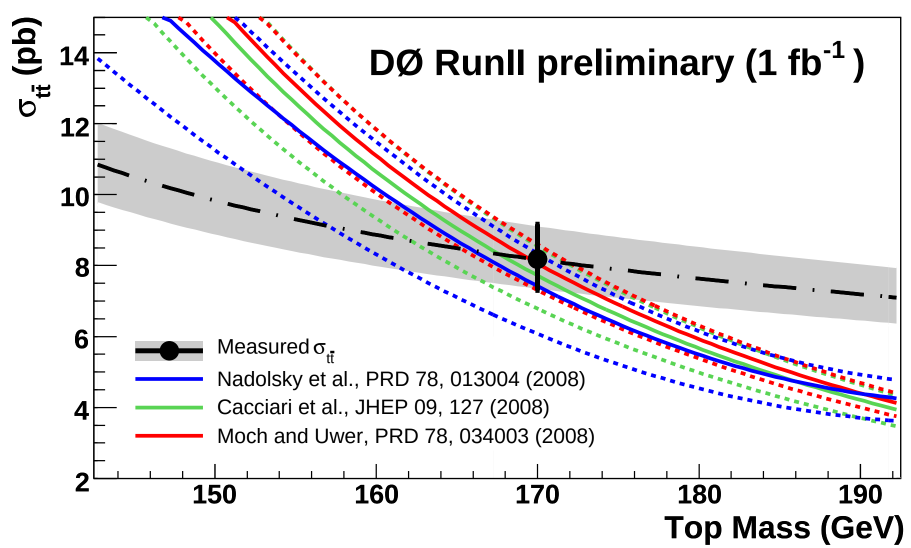
$$\mathrm{q} + \bar{\mathrm{q}} \longrightarrow \mathrm{Q} + \bar{\mathrm{Q}}$$
$$\mathrm{g} + \mathrm{g} \longrightarrow \mathrm{Q} + \bar{\mathrm{Q}}$$

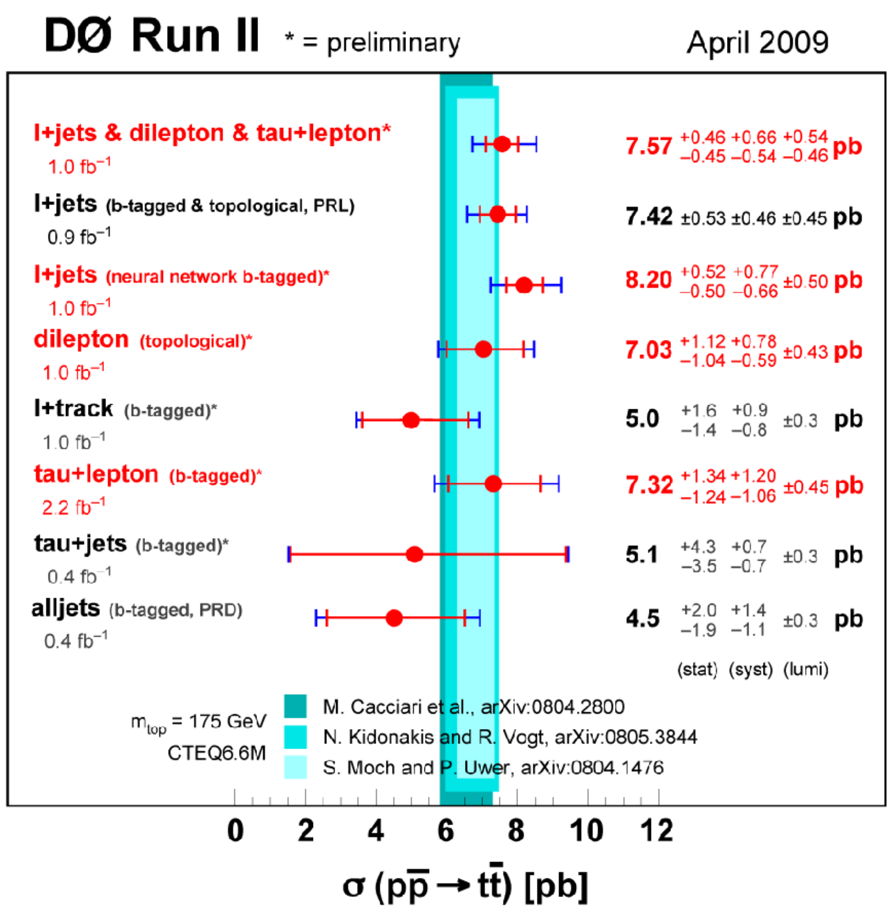


- NLO in QCD Nason, Dawson, Ellis '88; Beenakker, Smith, van Neerven '89; Mangano, Nason, Ridolfi '92; Bernreuther, Brandenburg, Si, Uwer '04; . . .
  - $\mathrm{q}\bar{\mathrm{q}}$ and gg dominant at NLO; neglect $\mathrm{qg} \longrightarrow$ at NLO only $\mathcal{O}(1\%)$

Tevatron analyses

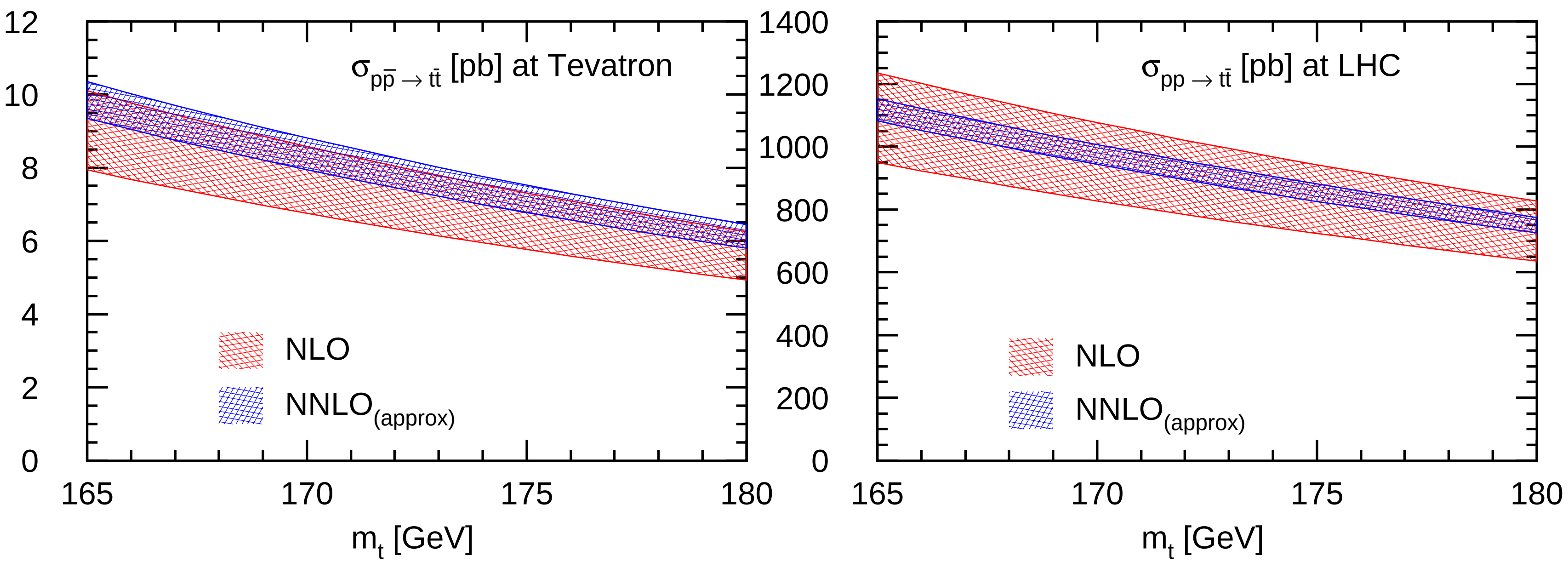
- Total cross section and different channels of Tevatron analyses (theory uncertainty band from scale variation)
- Determination of m_t from total cross section (slope $d\sigma/dm_t$)
  - e.g. DZero '09: NLO $m_t = 165.5^{+6.1}_{-5.9}$; NNLO $m_t = 169.1^{+5.9}_{-5.2}$; ...





LHC total cross section

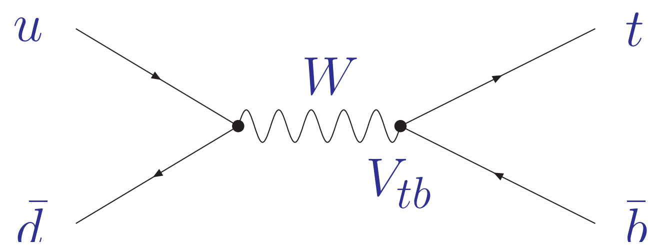
- NLO (with MRST2006 PDF set)
  - scale uncertainty $\mathcal{O}(10\%)$ $\oplus$ PDF uncertainty $\mathcal{O}(5\%)$
- $\text{NNLO}_{\text{approx}}$ (with MRST2006 PDF set)
  - scale uncertainty $\mathcal{O}(3\%)$ $\oplus$ PDF uncertainty $\mathcal{O}(2\%)$



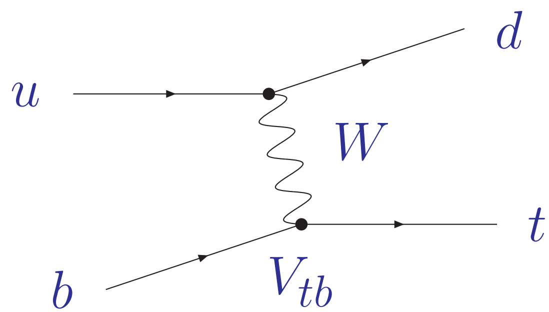
- Theory at NNLO matches anticipated experimental precision $\mathcal{O}(10\%)$

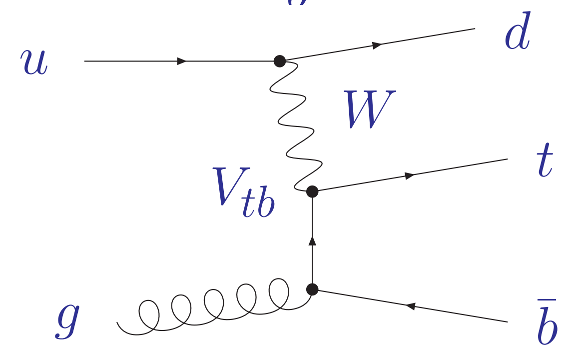
Single top-quark production

- Single-top production allows study of charged-current weak interaction of top quark
  - direct extraction of the CKM-matrix element V_{tb}
  - flagship measurement of Tevatron run II (control QCD bckgrd !)
- s-channel production



- t-channel production
  - bg-channel at NLO enhanced by gluon luminosity





- Large corrections from extensions of Standard Model
  - t-channel: anomalous couplings or flavor changing neutral currents
  - s-channel: charged “top-pion”, Kaluza-Klein modes of W or W‘-boson

Summary

Introduction to QCD and Electroweak Physics

- The big questions
- Basics of perturbative QCD
- QCD factorization for hard scattering
- Parton luminosity
- Jet cross sections at hadron colliders
- $W^{\pm}$ and Z-boson production at LHC
- Hadro-production of Top-Quarks

Outlook

– Higgs, Supersymmetry and beyond *Tuesday, August 04, 2009*

Literature

- Review
  - *Expectations at LHC from hard QCD*
    J. Phys. G: Nucl. Part. Phys. **35**, 073001 (2008) [arXiv:0803.0457] [hep-ph].