Physics of the Standard Model

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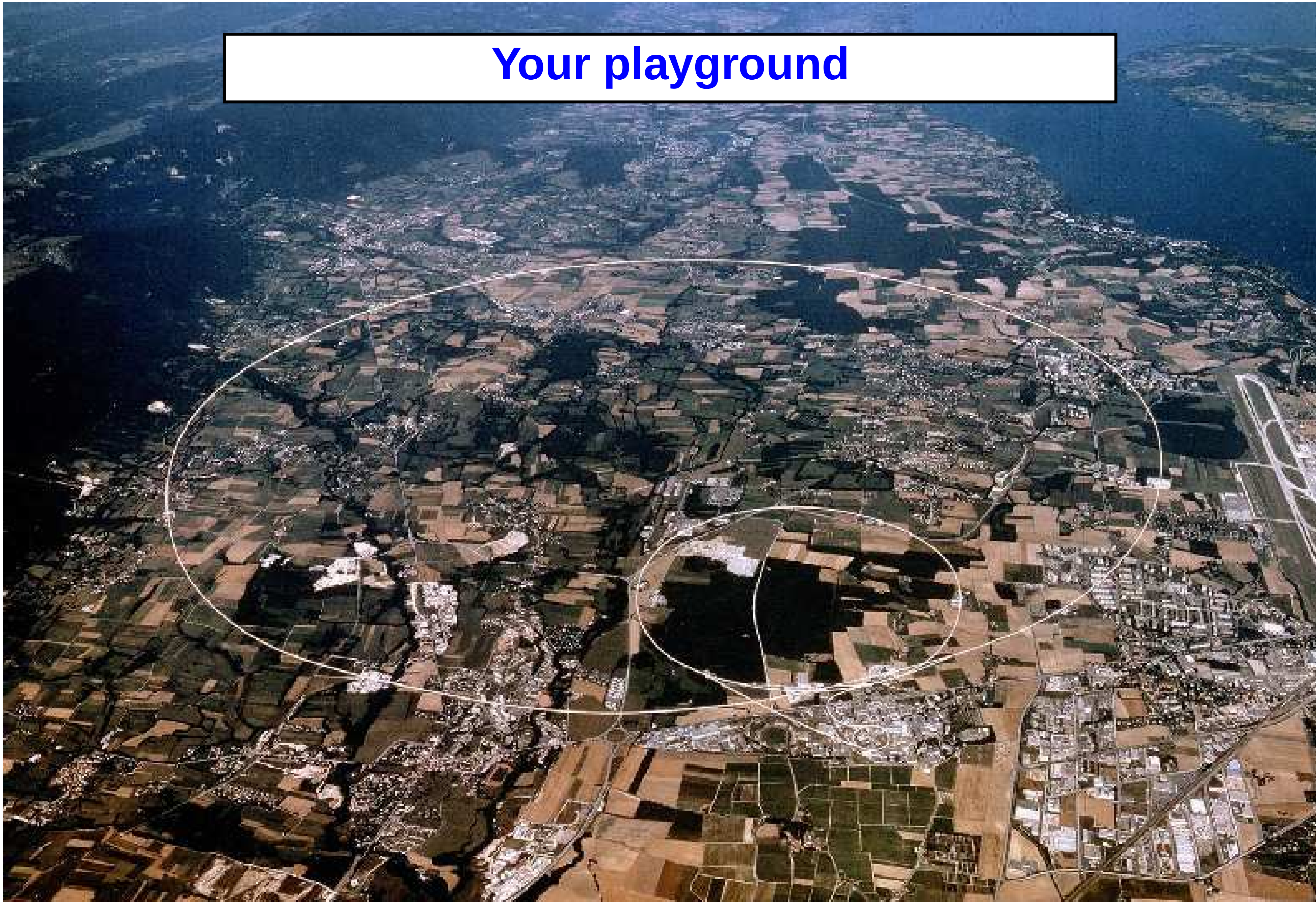
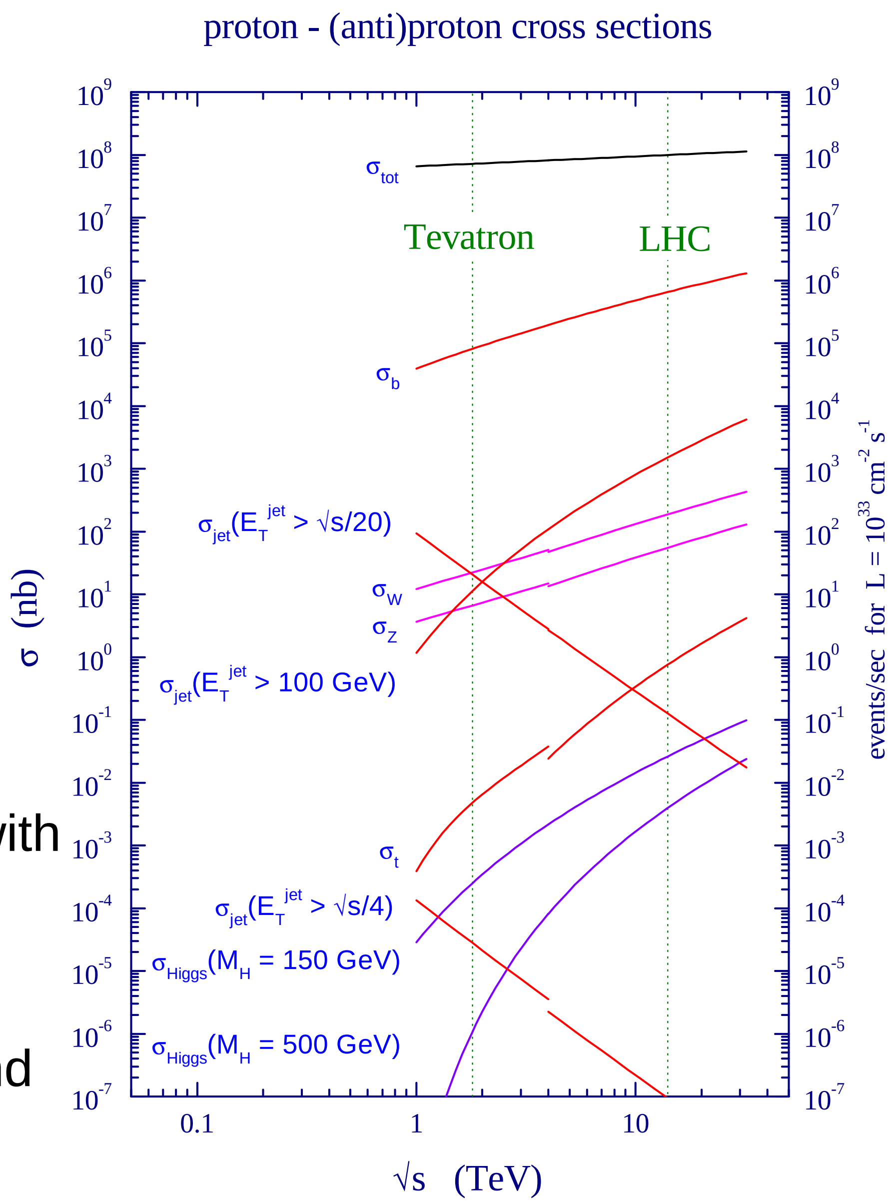
Your playground



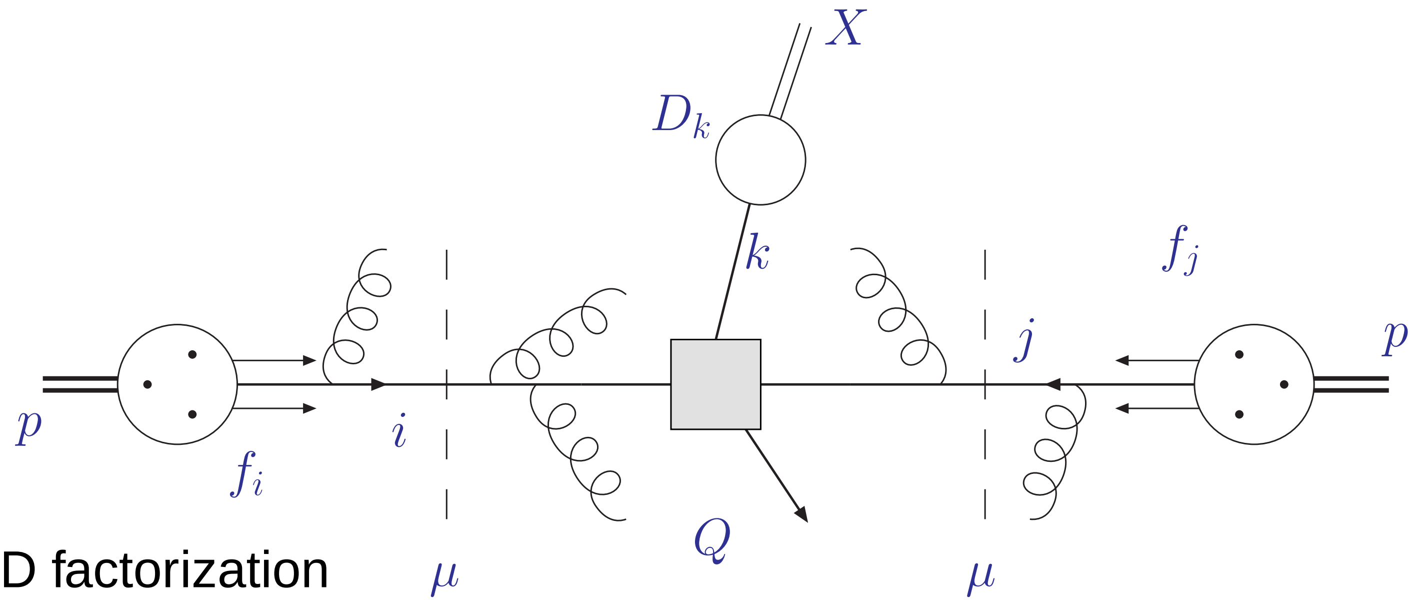
Proton-proton scattering

- Large rates expected for many Standard Model processes
  - b-quarks
  - $W^{\pm}$ and Z-bosons
  - jets (even with high p_t-cuts)
  - t-quarks
- New physics search requires precision predictions
  - Higgs production
  - superpartners in MSSM (neutralinos, charginos, squarks, gluinos, ...)
  - Kaluza-Klein modes in models with extra dimensions
- LHC will be a QCD machine
  - perturbative QCD is essential and established part of toolkit (we no longer “test” QCD)



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: $\frac{d}{d\ln\mu^2}\sigma_{pp\to X} = \mathcal{O}(\alpha_s^{l+1})$

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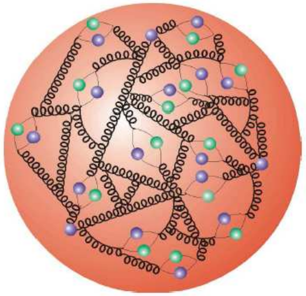
- Parton cross section $\hat{\sigma}_{ij\to k}$ calculable pertubatively in powers of α_s
  - constituent partons from incoming protons interact at short distances of order $\mathcal{O}(1/Q)$
- Parton luminosity $f_i \otimes f_j$
  - proton: very complicated multi-particle bound state
  - colliders: 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)
- NNLO (next-to-next-to-leading order)
  - selected results known (mostly inclusive kinematics)
- N^{3}LO (next-to-next-to-next-to-leading order)
  - very few . . .

Approaches to the calculation of σ_{had}

easy

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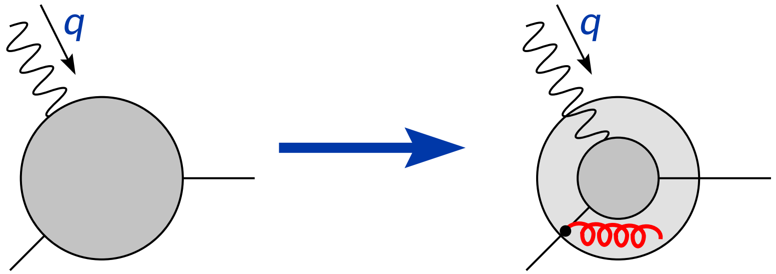
easy

$\leftarrow$ level of talk here

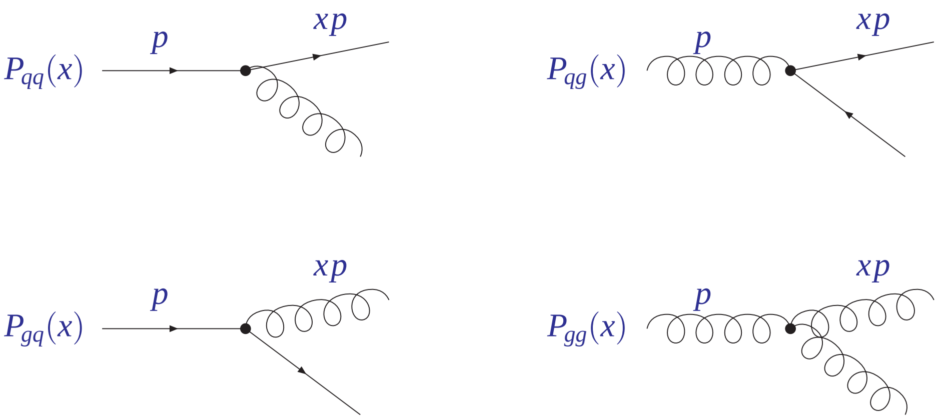
difficult

Parton luminosity

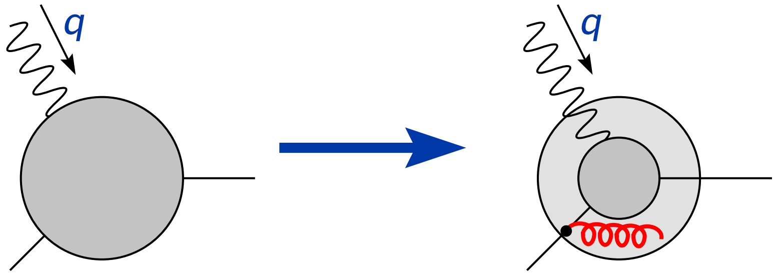


- Proton in resolution $1/Q \longrightarrow$ sensitive to lower momentum partons

- Feynman diagrams in leading order



Parton luminosity



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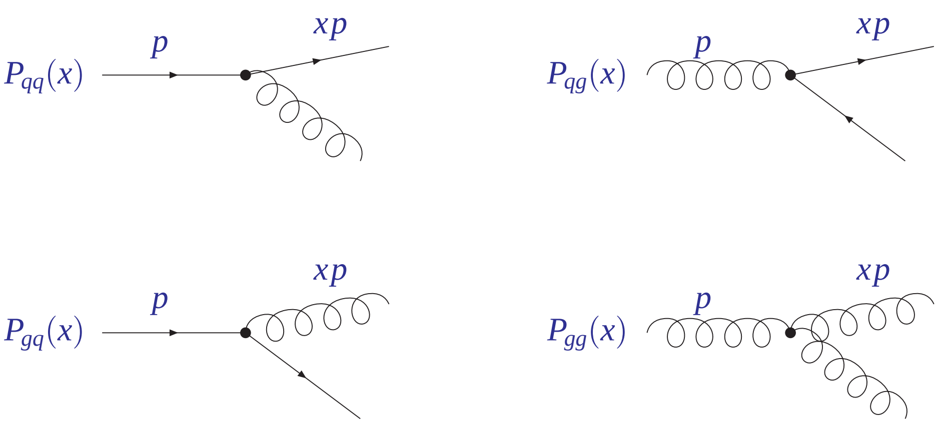


- Proton in resolution $1/Q \longrightarrow$ sensitive to lower momentum partons

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

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

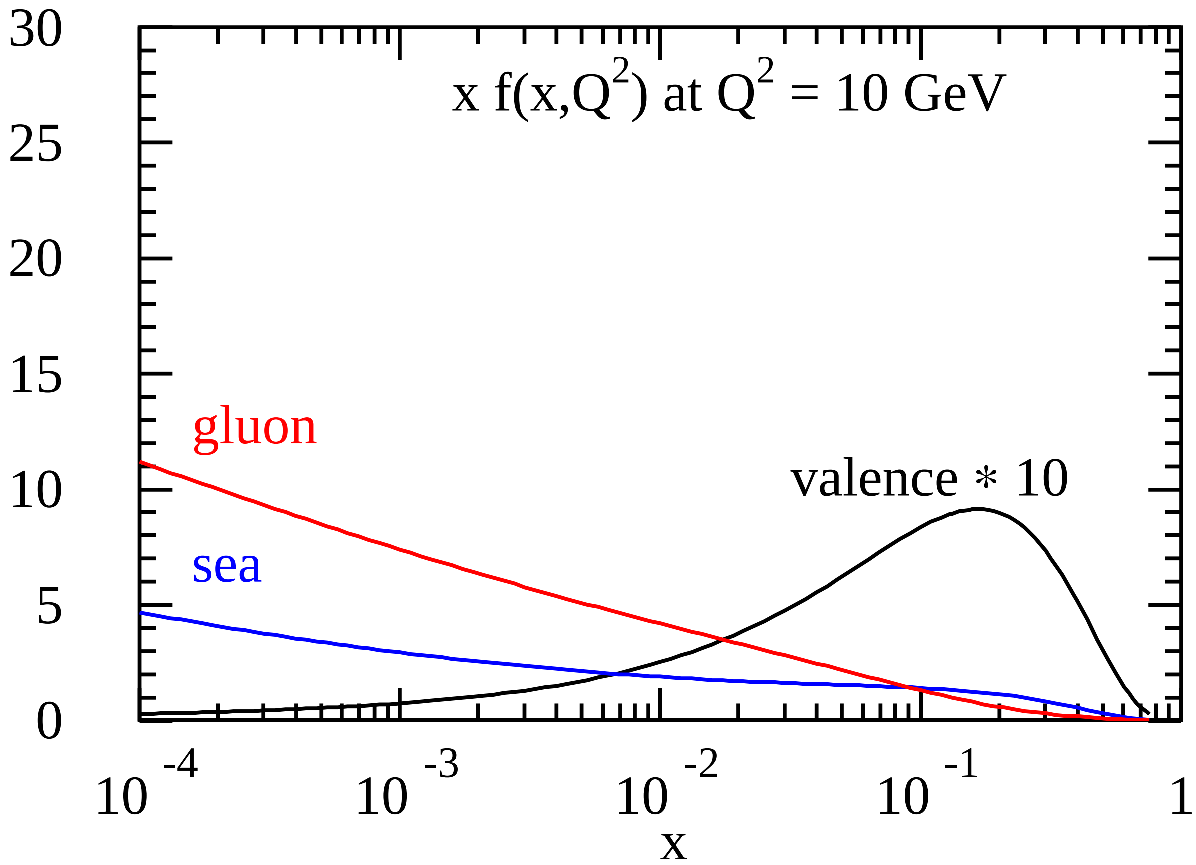
- Splitting functions P

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

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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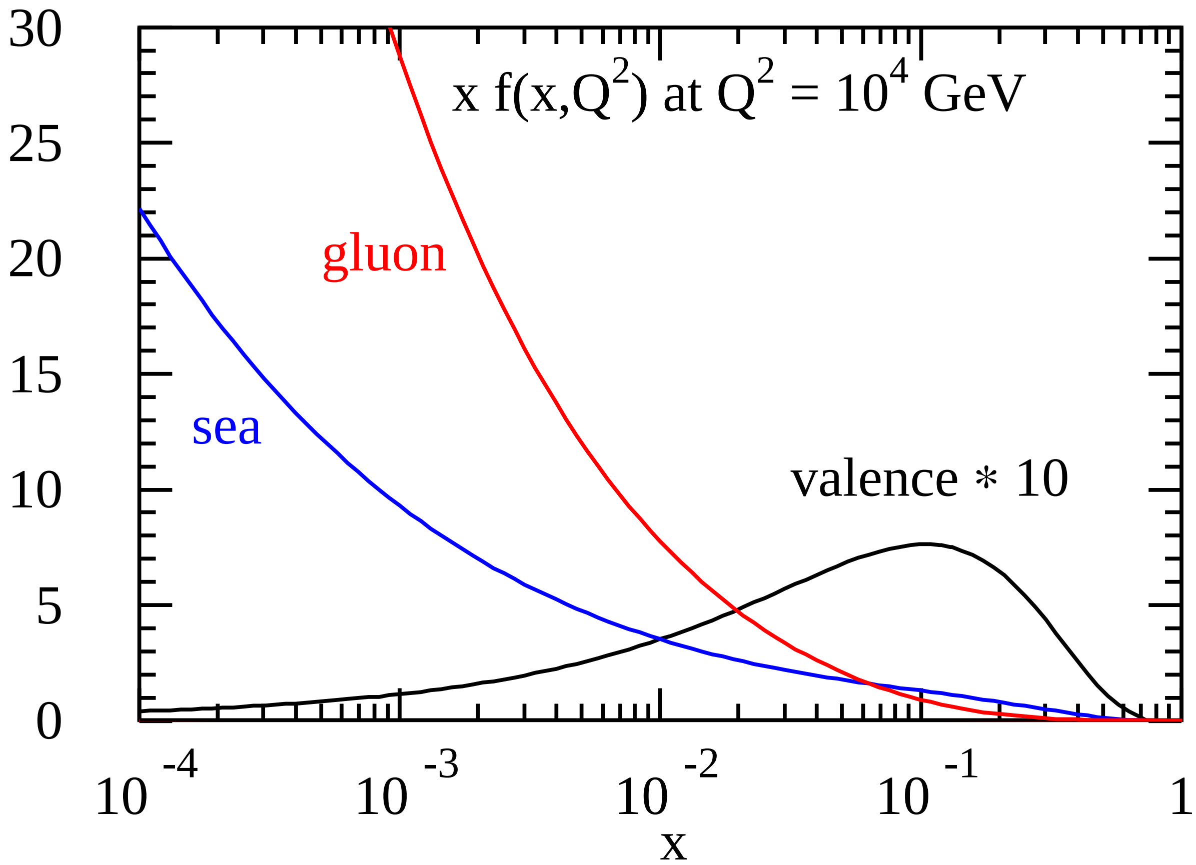

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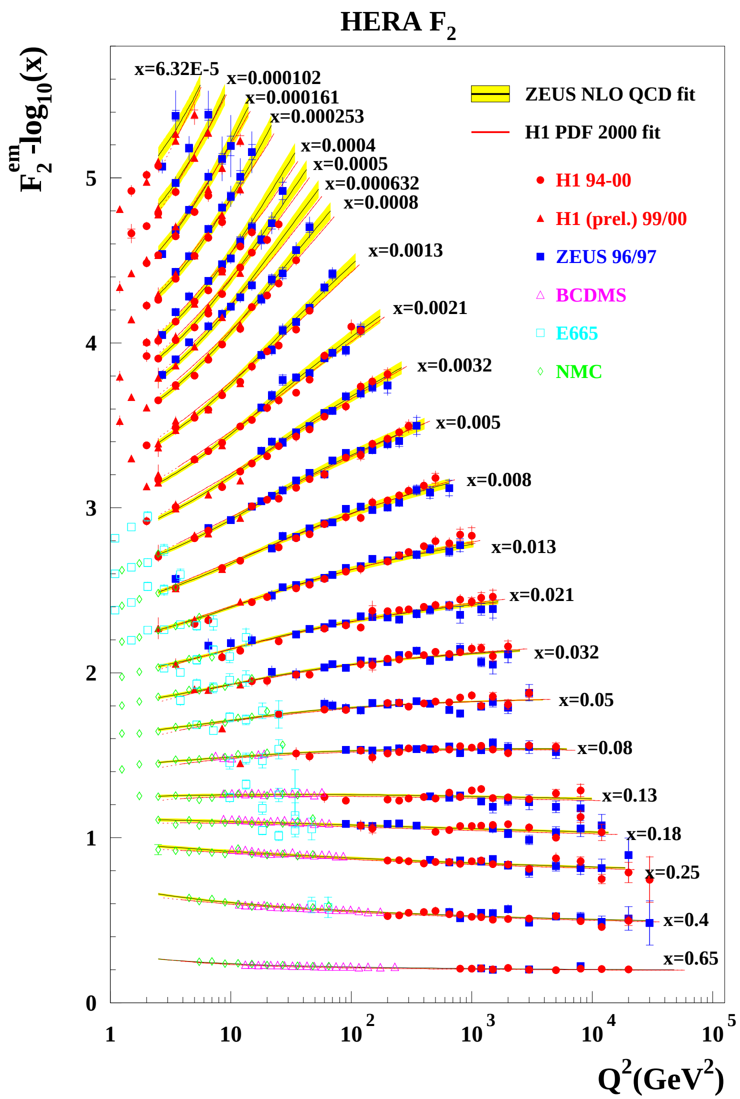
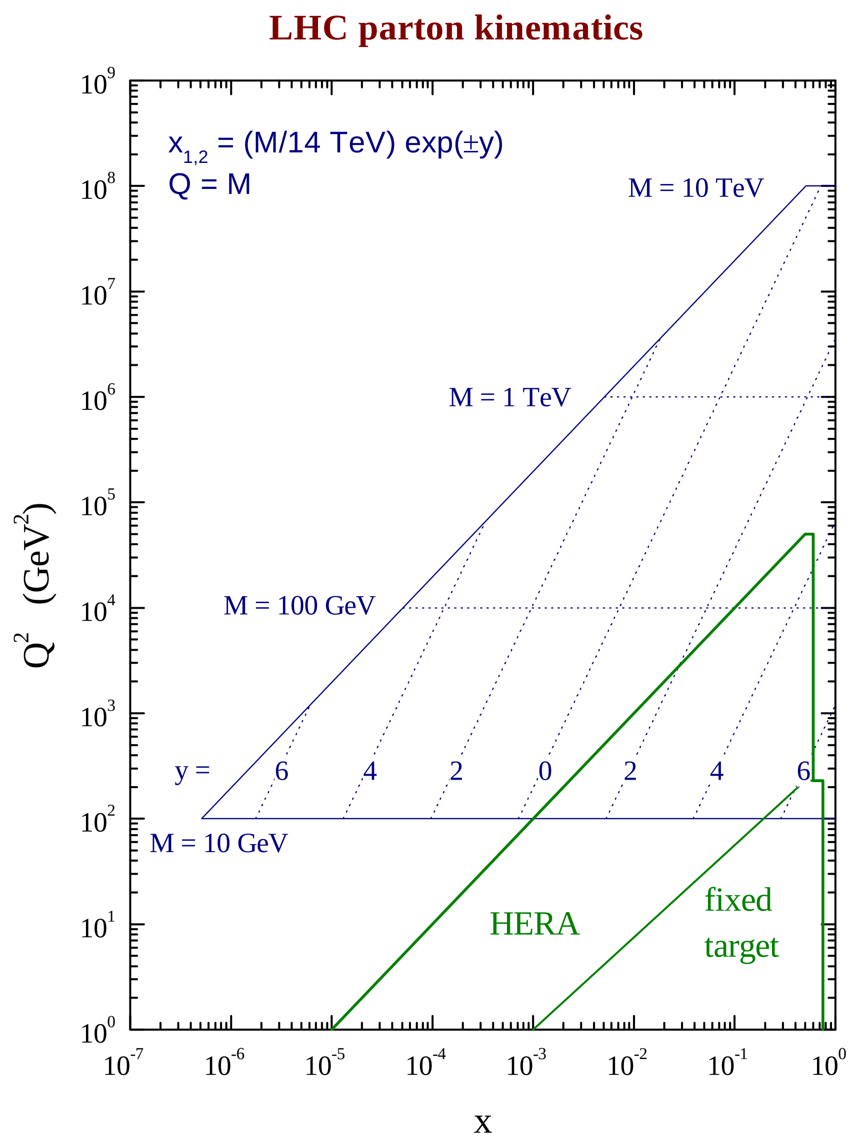
PDFs from HERA to LHC

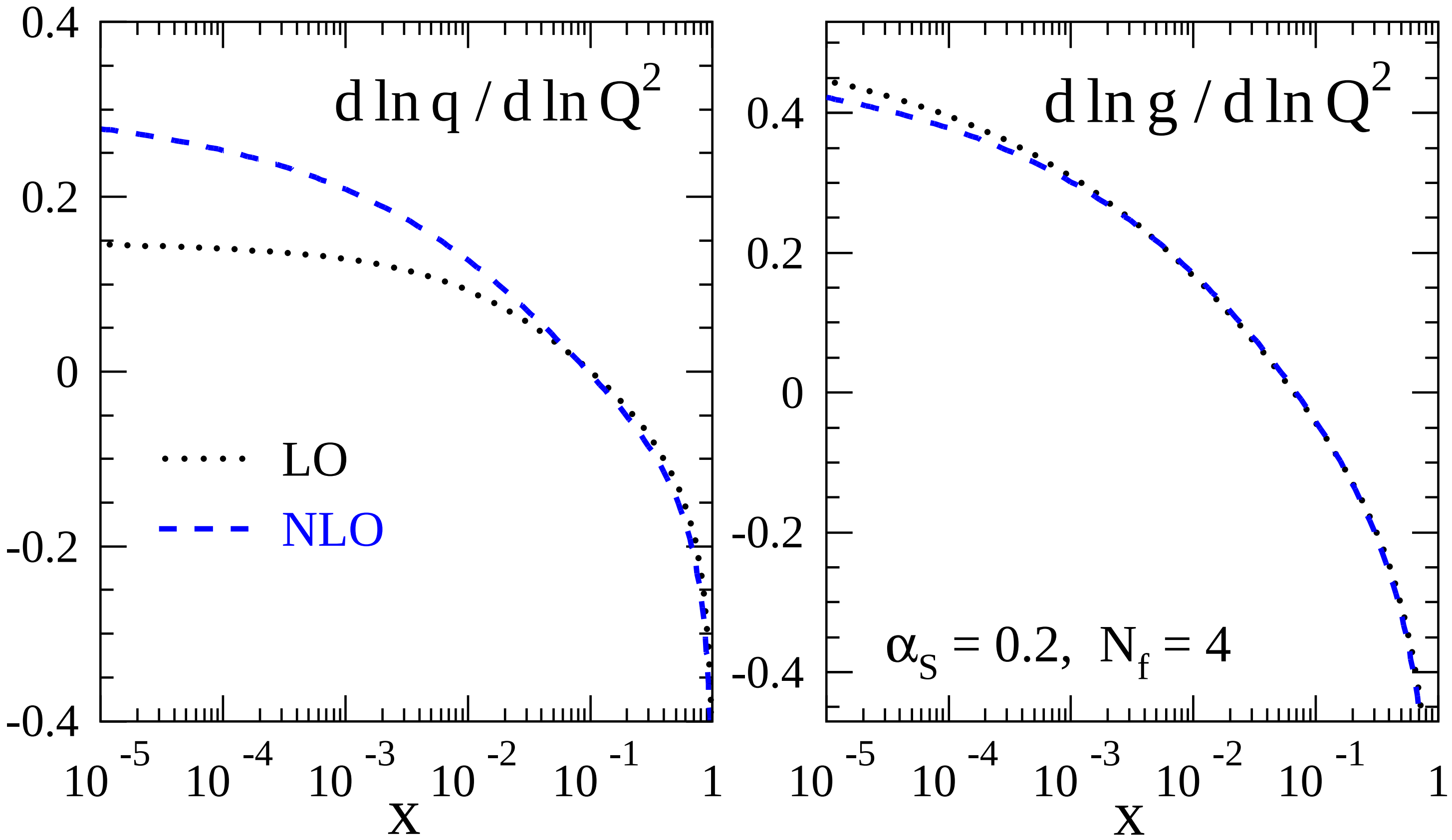




- Precision HERA data on F_2
- Scale evolution of PDFs in Q over two to three orders

Perturbative stability of evolution

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



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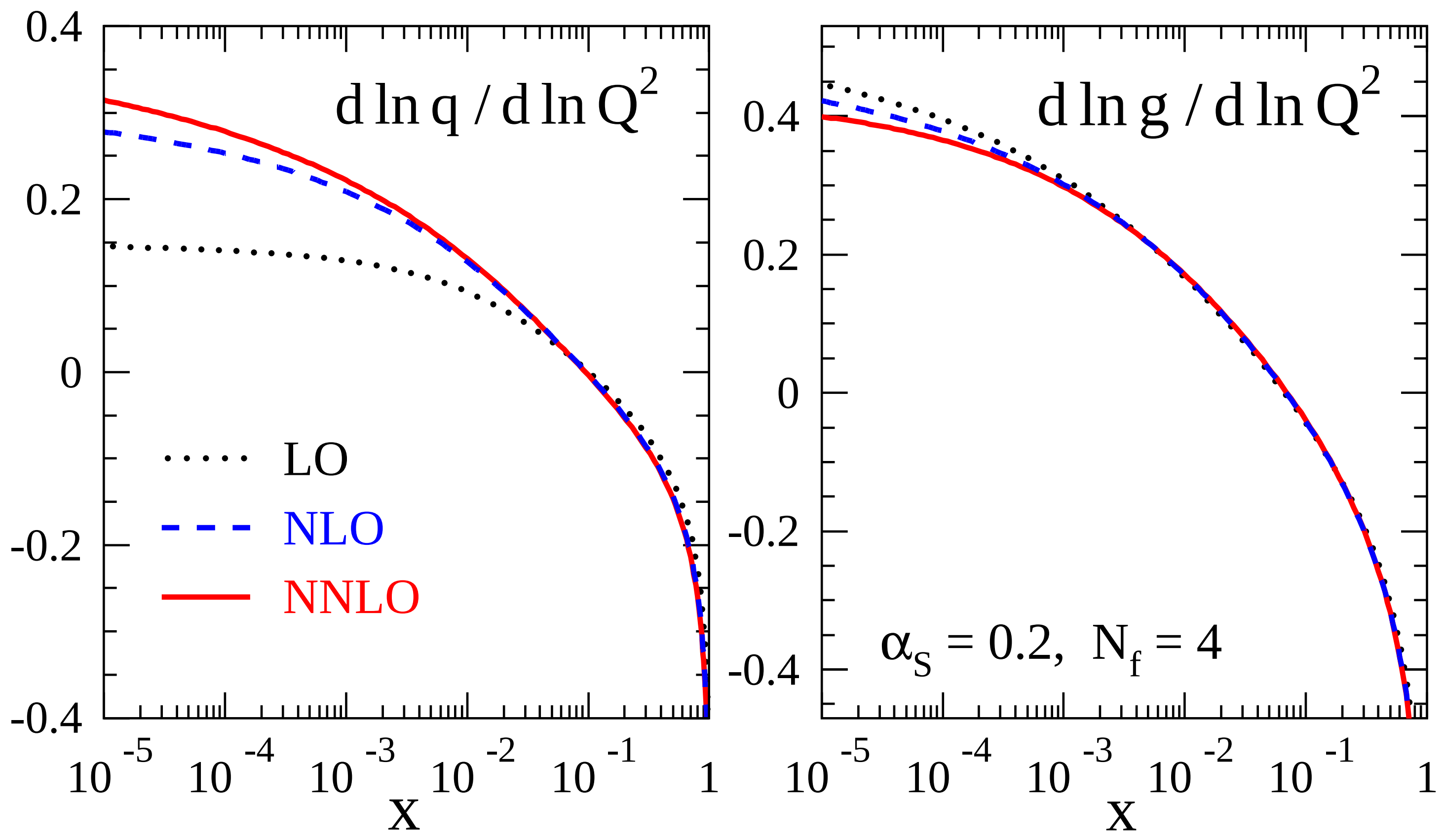
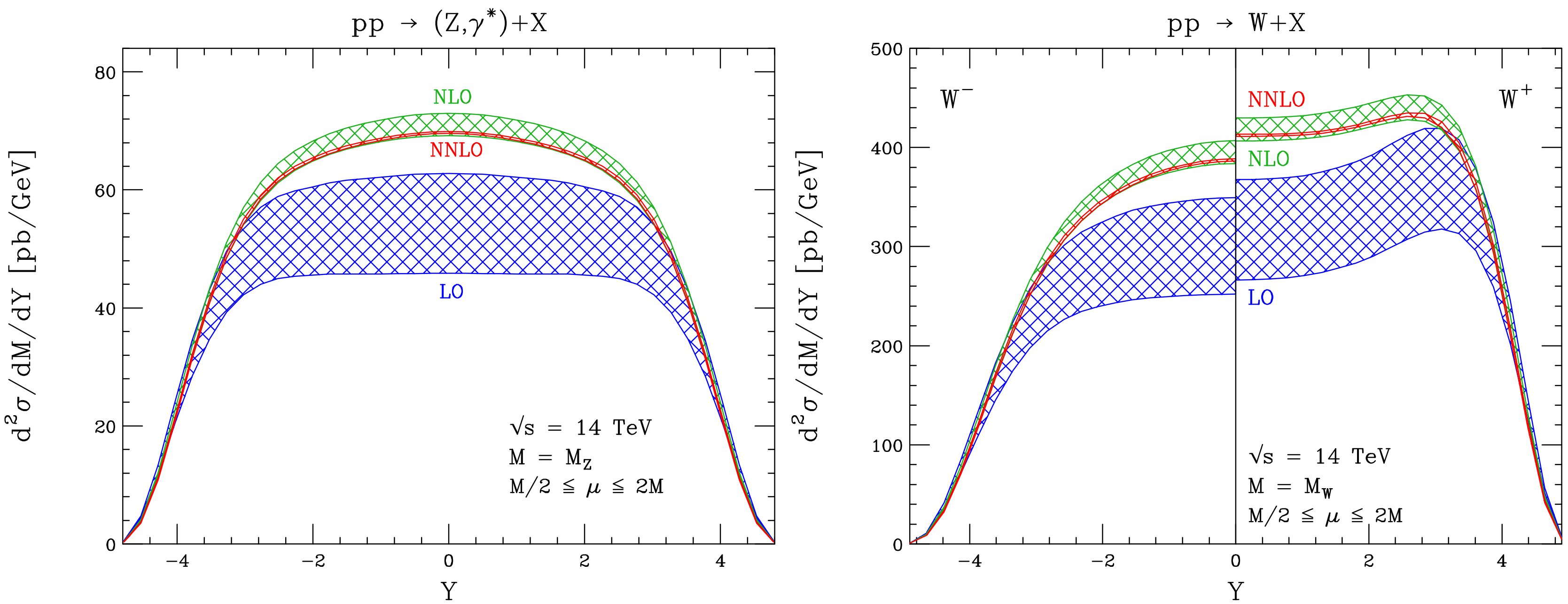


- Expansion very stable except for very small momenta $x \lesssim 10^{-4}$

Impact on precision of LHC predictions

- $W^{\pm}, Z$-boson rapidity distribution (scale variation $\frac{m_{W,Z}}{2} \leq \mu \leq 2m_{W,Z}$)

  Anastasiou, Petriello, Melnikov '05



- NNLO QCD theoretical uncertainties (renormalization / factorization scale) at level of 1% Dissertori et al. '05
  - one of the few cross sections known to NNLO in pQCD
- "Standard candle" process for parton luminosity

Updates of PDFs (exp)

- New experimental data
  - results from neutrino-nucleon DIS for strange quark PDFs ($s \neq \bar{s}$)
- Uncertainty on $\bar{u}$, $\bar{d}$ doubles from 1.5% to 3% at $Q^2 \simeq M_W^2$ MSTW '07
  - s, $\bar{s}$ feed into F_2 NC DIS constraint $4/9(u + \bar{u}) + 1/9(d + \bar{d} + s + \bar{s})$

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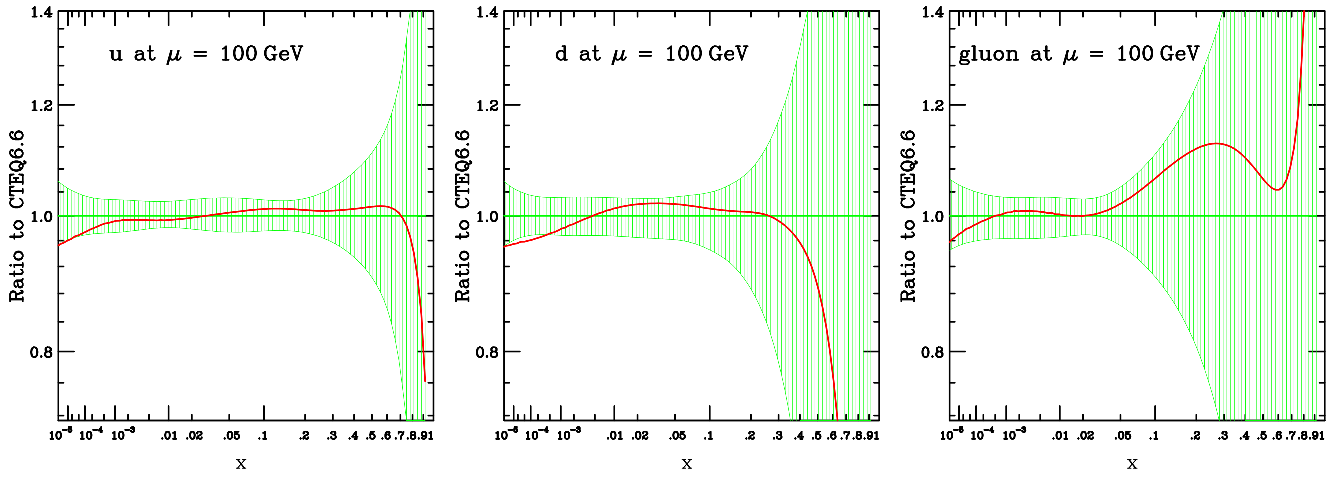
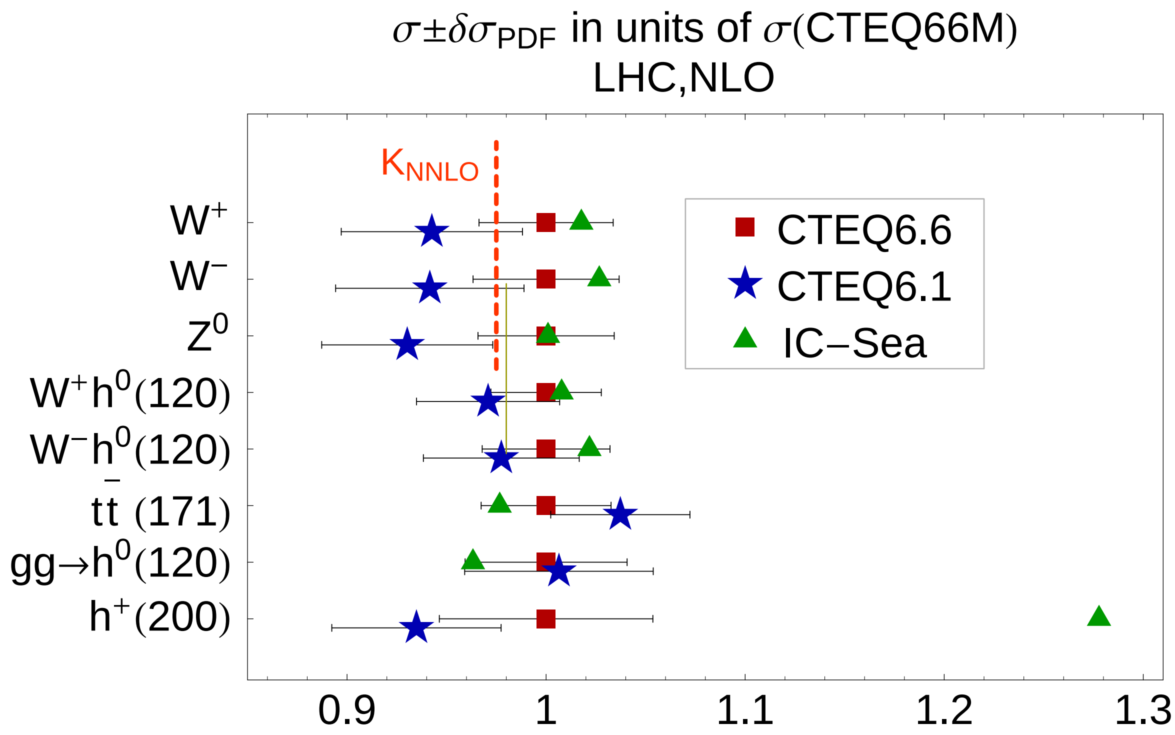
Updates of PDFs (th)

- Improved heavy quark (charm) threshold
  - matching consistent with QCD factorization CTEQ '08
- Significant changes due to larger light flavor PDFs



Cross sections at LHC

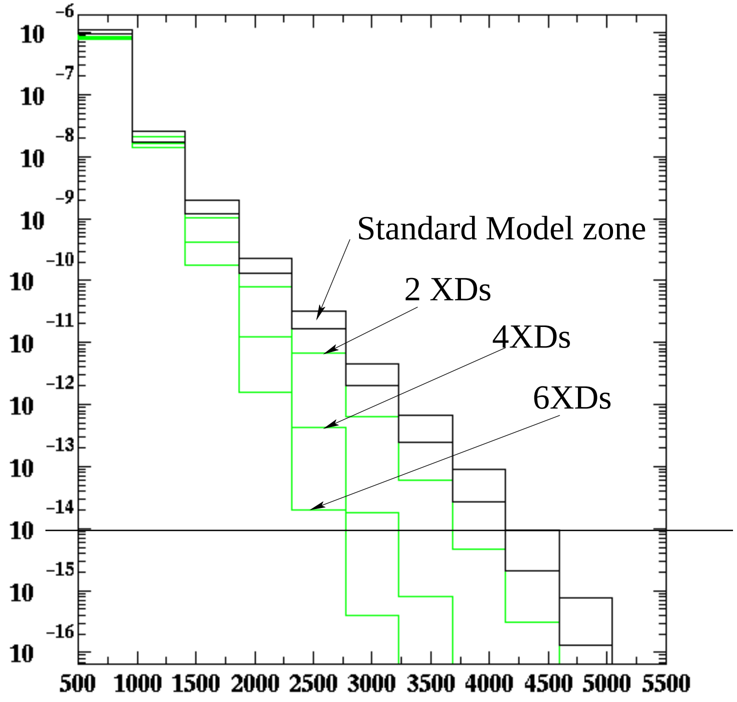


- Predictions for $W^{\pm}/Z$ cross sections at LHC shift by 8% between PDF sets CTEQ6.6 and CTEQ6.1 (improved theory!)
  - sensitivity to PDFs in the $x \sim 10^{-3}$ range
- $W^{\pm}/Z$-ratio golden calibration measurement

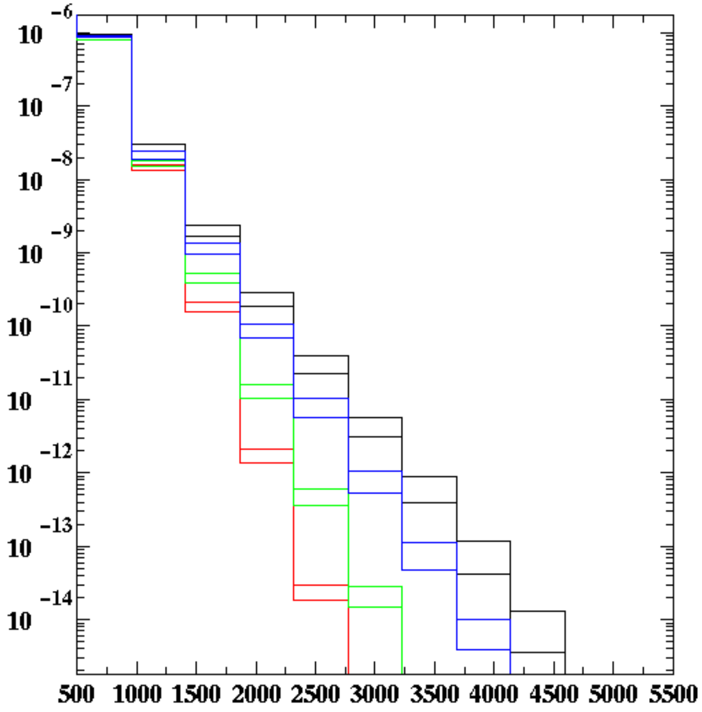
Large extra dimensions

- Sensitivity of LHC dijet cross section to large extra dimensions Ferrag '04
  - large extra dimensions accelerate running of α_s as compactification scale M_c is approached
- PDF uncertainties
  - potential sensitivity to M_c reduced from 6 TeV to 2 TeV

$M_c = 2$ TeV no PDF error

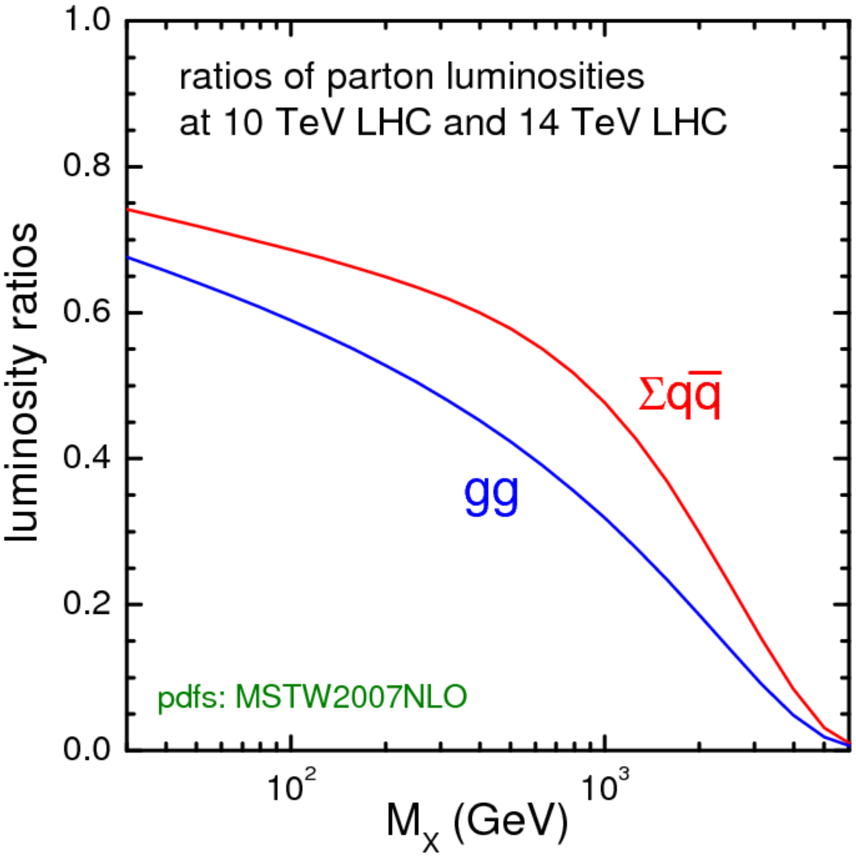


$M_c = 2$ TeV with PDF error



Initial LHC run at 10 TeV

- Cross section estimates through ratio of parton luminosities
  Stirling at DIS 2008
  - less phase space for production of high mass objects at 10 TeV



- Cross section is reduced by $\mathcal{O}(50)\%$ for masses below ~ 200 GeV (dependent on process)
  - e.g. production of $t\bar{t}$-pairs reduced by factor of $\mathcal{O}(2)$
- Stronger reduction for scales of $\mathcal{O}(2-3)$ TeV

Parton cross sections

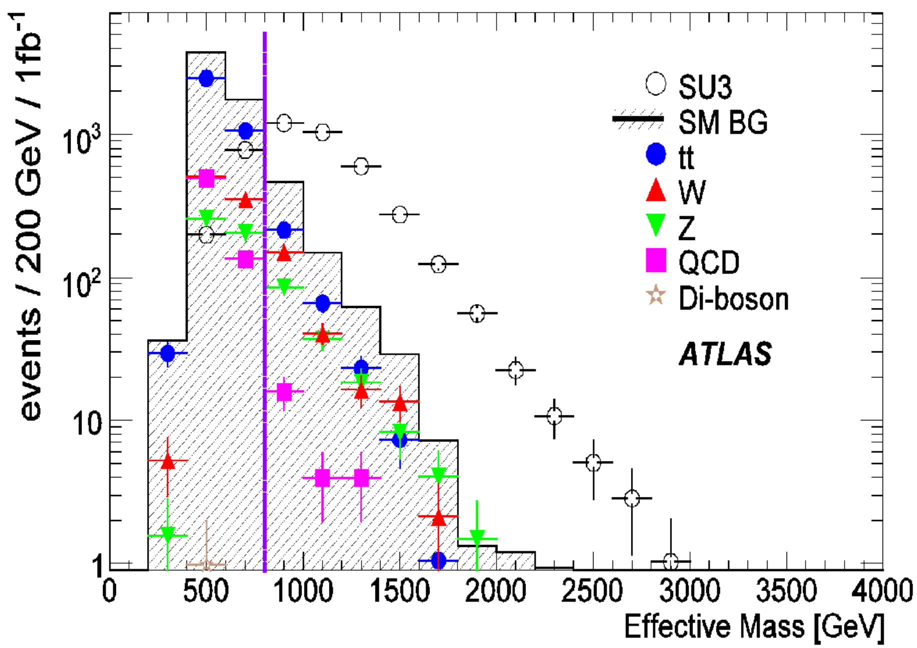
How precise are the predictions?

- 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 $\Delta(\alpha_s^{\mathrm{LO}}) \simeq 10\%$ gives $\Delta(\sigma^{\mathrm{LO}}) \simeq 40\%$

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
$pp \to t\bar{t}b\bar{b}$	$t\bar{t}H$	
$pp \to t\bar{t} + 2$ 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	
$pp \to VVV$	SUSY trilepton	ZZZ, WWZ

Les Houches 2005 [hep-ph/0604120]

Original experimenter's wishlist

Tevatron Run II Monte Carlo workshop April 2001

Run II Monte Carlo Workshop, April 2001

Single boson	Diboson	Triboson	Heavy flavour
$W + \leq 5j$	$WW + \leq 5j$	$WWW + \leq 3j$	$t\bar{t} + \leq 3j$
$W + b\bar{b} + \leq 3j$	$WW + b\bar{b} + \leq 3j$	$WWW + b\bar{b} + \leq 3j$	$t\bar{t} + \gamma + \leq 2j$
$W + c\bar{c} + \leq 3j$	$WW + c\bar{c} + \leq 3j$	$WWW + \gamma\gamma + \leq 3j$	$t\bar{t} + W + \leq 2j$
$Z + \leq 5j$	$ZZ + \leq 5j$	$Z\gamma\gamma + \leq 3j$	$t\bar{t} + Z + \leq 2j$
$Z + b\bar{b} + \leq 3j$	$ZZ + b\bar{b} + \leq 3j$	$WZZ + \leq 3j$	$t\bar{t} + H + \leq 2j$
$Z + c\bar{c} + \leq 3j$	$ZZ + c\bar{c} + \leq 3j$	$ZZZ + \leq 3j$	$t\bar{b} + \leq 2j$
$\gamma + \leq 5j$	$\gamma\gamma + \leq 5j$		$b\bar{b} + \leq 3j$
$\gamma + b\bar{b} + \leq 3j$	$\gamma\gamma + b\bar{b} + \leq 3j$		
$\gamma + c\bar{c} + \leq 3j$	$\gamma\gamma + c\bar{c} + \leq 3j$		
	$WZ + \leq 5j$		
	$WZ + b\bar{b} + \leq 3j$		
	$WZ + c\bar{c} + \leq 3j$		
	$W\gamma + \leq 3j$		
	$Z\gamma + \leq 3j$		

Why are one-loop corrections difficult ?

- Outline of a generic NLO calculation

Real corrections
- subtractions (IR-divergent)

Virtual corrections
+ 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

LO

- Efficient techniques for computing tree amplitudes exist
  - recursion relations Berends, Giele '87

NLO

- Straightforward in principle – hard in practice with known bottlenecks
  - one-loop virtual corrections (tensor integrals)

$$I^{\mu_1,\mu_2,\ldots}(k_1,\ldots) = \int d^D p_1 \frac{p_1^{\mu_1} p_2^{\mu_2} \ldots}{(p_1^2 - m_1^2)((p_1 - k_1)^2 - m_2^2) \ldots}$$

- Alternative methods for tensor reduction
  - improved Passarino-Veltman; multi-loop inspired techniques; sector decomposition + contour deformation; numerical approach to loop integration; . . .
- **New** recursive on-shell approach makes use of **well-known** methods
  - colour ordering; helicity amplitudes; supersymmetry; unitarity; factorization of amplitudes
- Unitarity: fusing rules for amplitudes (sewing of tree level amplitudes) Bern, Dixon, Dunbar, Kosower '94; . . .

Complete NLO results

- NLO cross sections for $2 \to 3$ processes (e.g. for hadron colliders)

$pp \to 3$jets, $\gamma\gamma+$jet, $V+2$jets, $t\bar{t}H$, $b\bar{b}H$, $t\bar{b}H$, $b\bar{b}V$, HHH, $H+2$jets, $VV+2$jets (VBF)

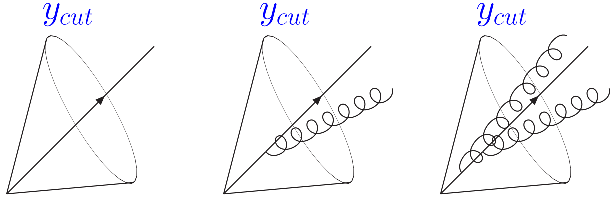
Bern et al.; Kunszt et al.; Kilgore, Giele; Campbell et al.; Nagy; Del Duca et al.; Campbell, Ellis; Beenakker et al.; Dawson et al.; Dittmaier et al.; Peng et al.; Plehn, Rauch; Febres Cordero et al.; Jäger et al.; Ciccolini et al. '96-'07

  - $pp \to t\bar{t} +$ jet at NLO Dittmaier, Uwer, Weinzierl '07
    $pp \to WW +$ jet at NLO Dittmaier, Kallweit, Uwer '07; Campbell, Ellis, Zanderighi '07
    $pp \to ZZZ$ at NLO Lazopoulos, Melnikov, Petriello '07
    $pp \to WWZ$ at NLO Hankele, Zeppenfeld '07

- $2 \to 4$ processes (current technical frontier)
  - QCD corrections to $\gamma\gamma \to t\bar{t}b\bar{b}$ Guo, Ma, Han, Zhang, Jing '07

Case for NNLO

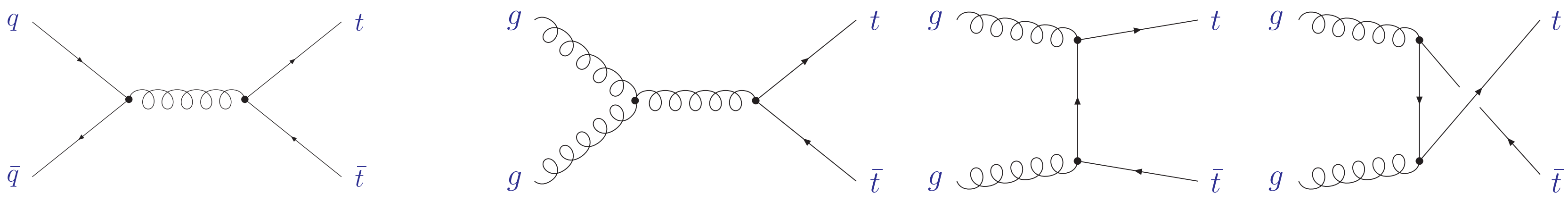
- Hadronic di-jets: large statistics even with high-p_T cuts
  - gluon jets constrain gluon PDF at medium/large x
  - searches for quark sub-structure (di-jet angular correlations)
- NNLO for di-jets important for scale uncertainty, PDF determination, modelling of jets, ...



- Calculation of NNLO cross sections
  - cancellation of infrared divergencies highly non-trivial
  - (two-loop) virtual amplitudes
    Anastasiou, Bern, v.d.Bij, De Freitas, Dixon, Ghinculov, Glover, Oleari, Schmidt, Tejeda-Yeomans, Wong '01-'04 and Garland, Gehrmann, Glover, Koukoutsakis, Remiddi, '02; S.M., Uwer, Weinzierl '02
  - numerical phase space integration very difficult
    Anastasiou, Del Duca, Frixione, Gehrmann, Gehrmann-De Ridder, Glover, Grazzini, Heinrich, Kilgore, Melnikov, Petriello, Somogyi, Trócsányi, Weinzierl '03-'08
  - major milestone $e^+e^- \to 3$ jets complete
    Gehrmann, Gehrmann-De Ridder, Glover, Heinrich '07

Top-quark production

- LHC will accumulate very high statistics for $t\bar{t}$-pairs
  - low luminosity run: $8 \cdot 10^6$ events/year (high luminosity run: 10 times more)
  - mass measurement $\Delta m_t = \mathcal{O}(1)$GeV constrains Standard Model Higgs mass M_H
  - top-quark spin correlations and searches for anomalous couplings
- Top-quarks make up large part of background for Higgs or new physics
  - Characteristic signatures (event reconstruction in many channels)
- Leading order Feynman diagrams



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

Total cross section (standard currency in theory)

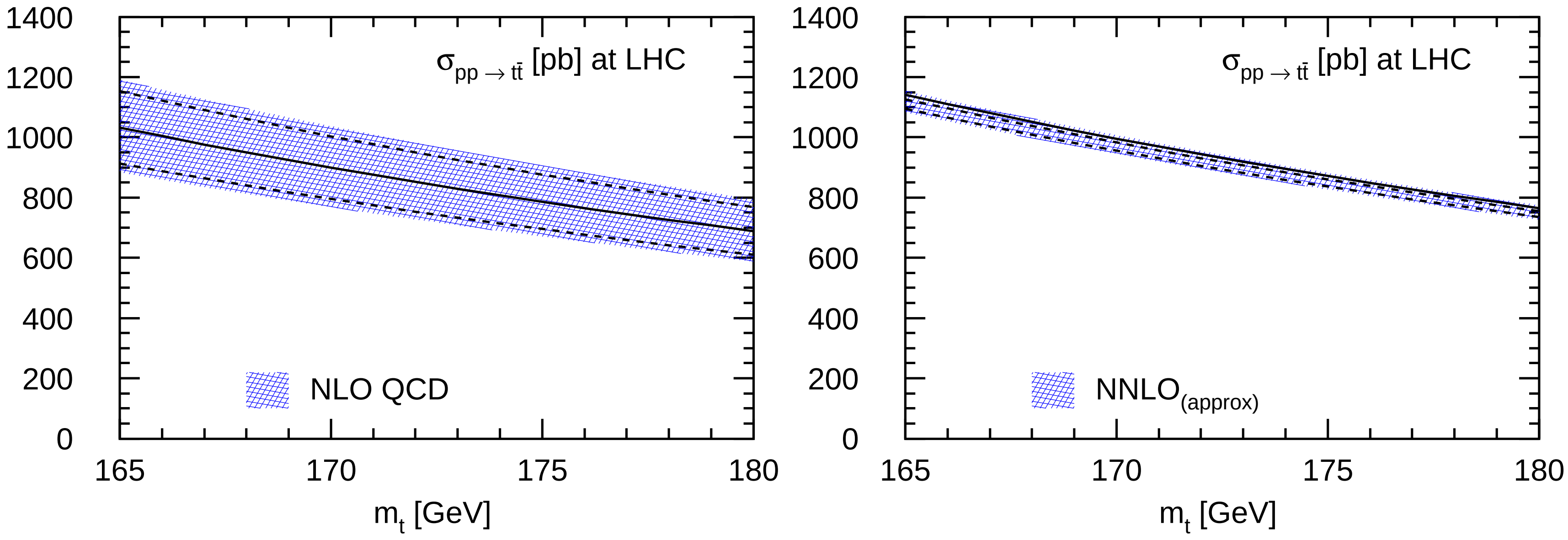
- Theory predictions
  - plain vanilla NLO QCD
    Nason, Dawson, Ellis '88; Beenakker, Smith, van Neerven '89; Mangano, Nason, Ridolfi '92; Bernreuther, Brandenburg, Si, Uwer '04; ...

Kinematical limits

- Small-mass limit $m^2 \ll s, t, u$
  - simple multiplicative relation between massive $\mathcal{M}^{(m)}$ and massless $\mathcal{M}^{(m=0)}$ amplitudes to all orders S.M., Mitov '06
  - full result for heavy-quark hadro-production at two loops in QCD in limit $m^2 \ll s, t, u$ S.M., Czakon, Mitov '07
- Threshold at $s \simeq 4m^2$
  - parton cross section exhibits Sudakov-type logarithms $\ln(\beta)$ with velocity of heavy quark $\beta = \sqrt{1 - 4m^2/s}$ at n$^{\mathrm{th}}$-order: $\alpha_s^n \ln^{2n}(\beta)$
  - NNLO corrections near threshold S.M., Uwer '08
    (all powers of $\ln \beta$ and Coulomb corrections plus exact scale dependent $\ln(\mu/m)$-terms)

LHC total cross section

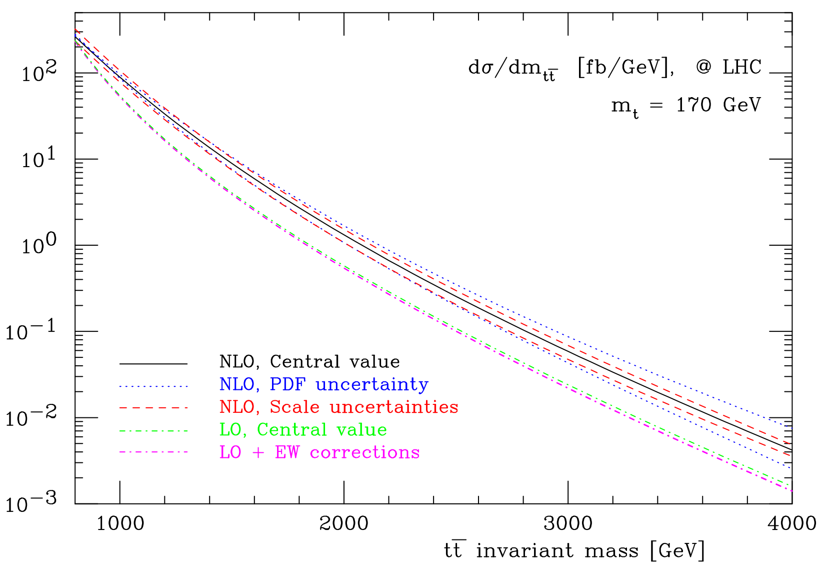
- NLO (with CTEQ6.5 PDF set)
  - scale uncertainty $\mathcal{O}(10\%)$ $\oplus$ PDF uncertainty $\mathcal{O}(5\%)$
- NNLO$_{\text{approx}}$ (with MRST2006 PDF set)
  - scale uncertainty $\mathcal{O}(3\%)$ $\oplus$ PDF uncertainty $\mathcal{O}(2\%)$

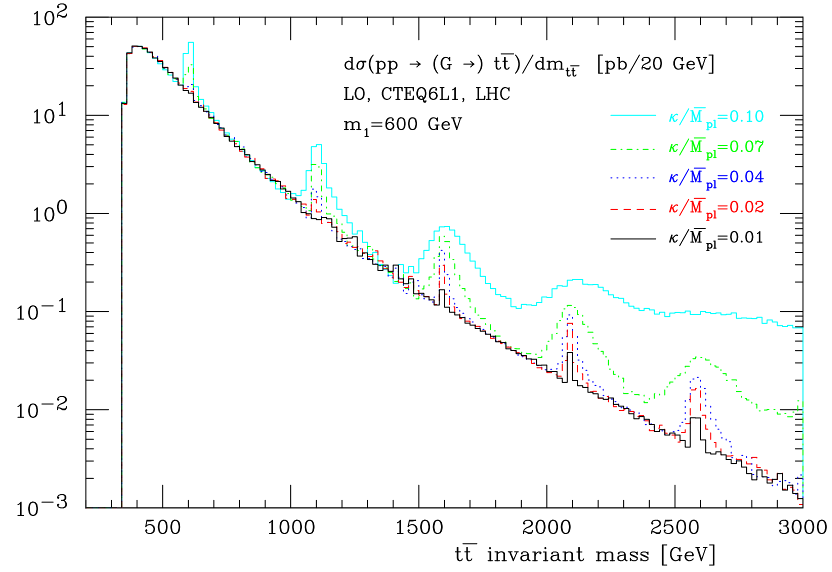


- Theory at NNLO matches anticipated experimental precision $\mathcal{O}(10\%)$

Invariant mass distribution

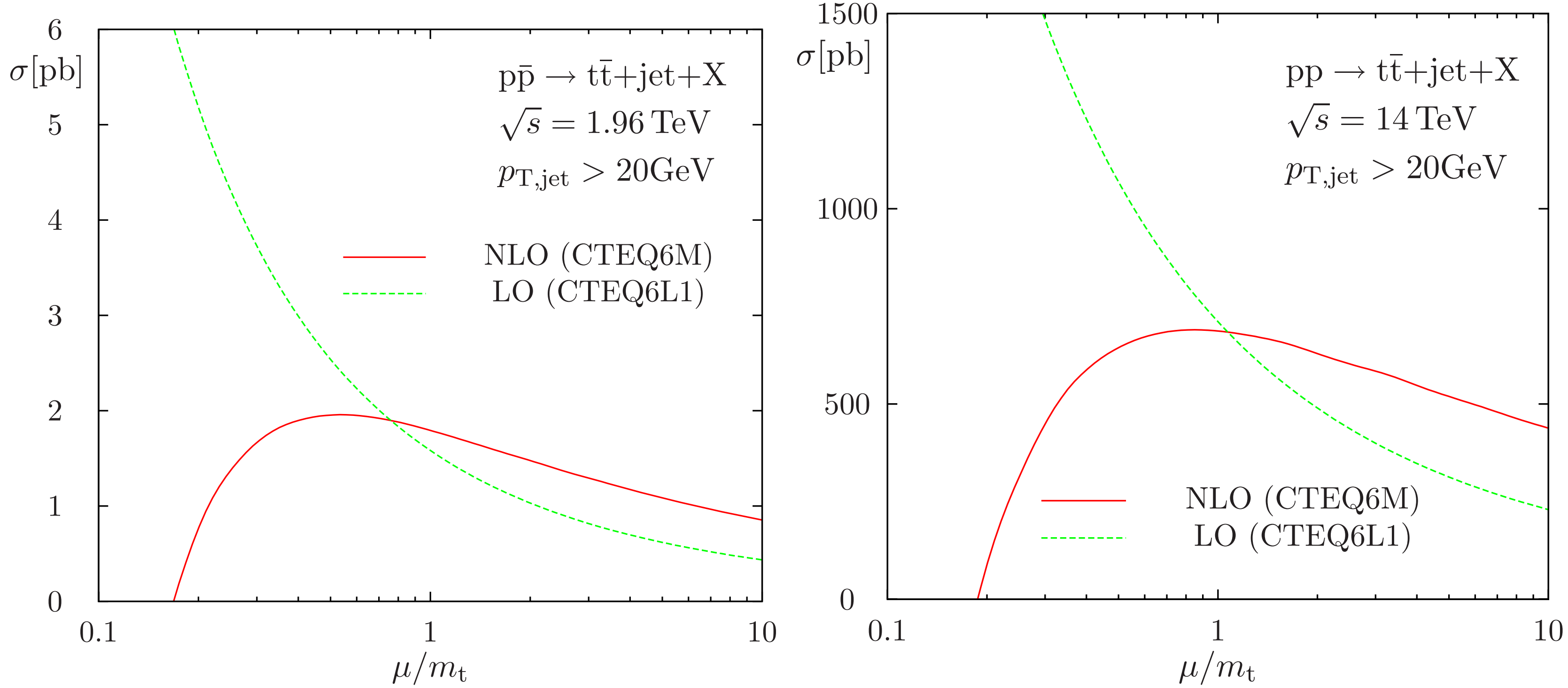
- Differential distribution in top-quark pair invariant $M_{t\bar{t}}$





- Left: the $t\bar{t}$ invariant mass spectrum at LHC with NLO electroweak corrections
- Right: s-channel graviton exchange in $t\bar{t}$ invariant mass spectrum at LHC Frederix, Maltoni '07
  - Kaluza-Klein resonances in an extra dimensions model

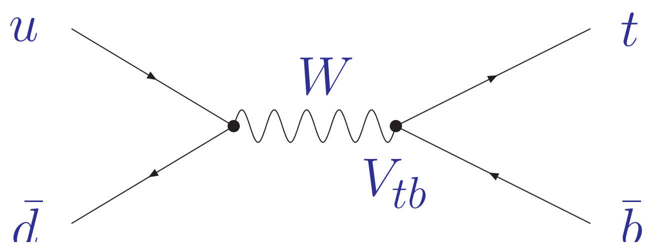
$t\bar{t}+$ jet production



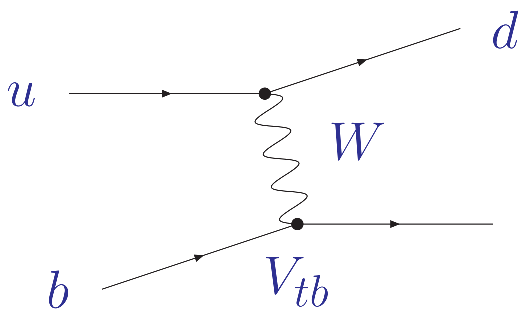
- Impressive state-of-the-art NLO QCD calculation
  Dittmaier, Uwer, Weinzierl '07
- Much improved scale dependence
- Differential distributions underway (will test parton shower predictions)

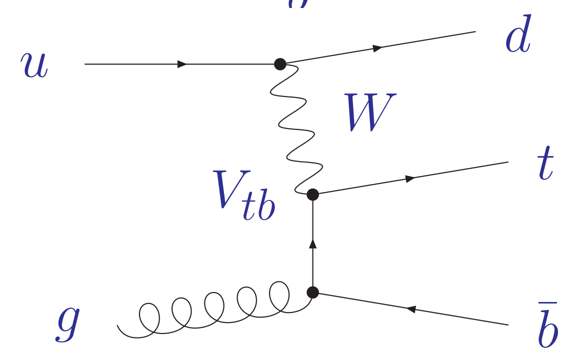
Single top-quark production

- 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



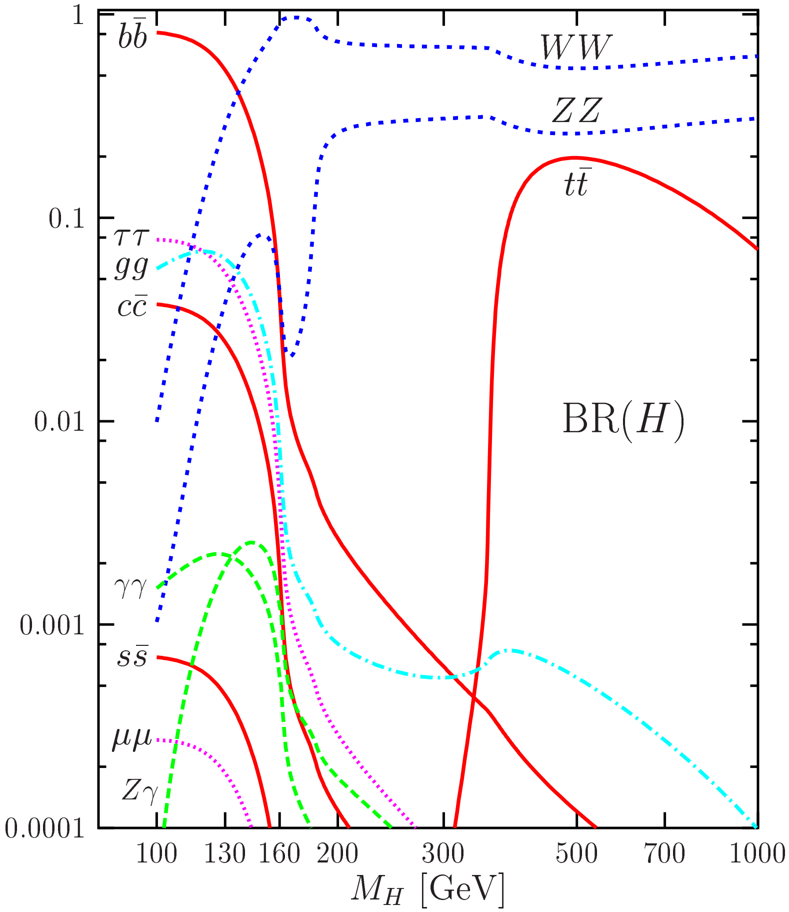
- t-channel production
  - bg-channel at NLO enhanced by gluon luminosity

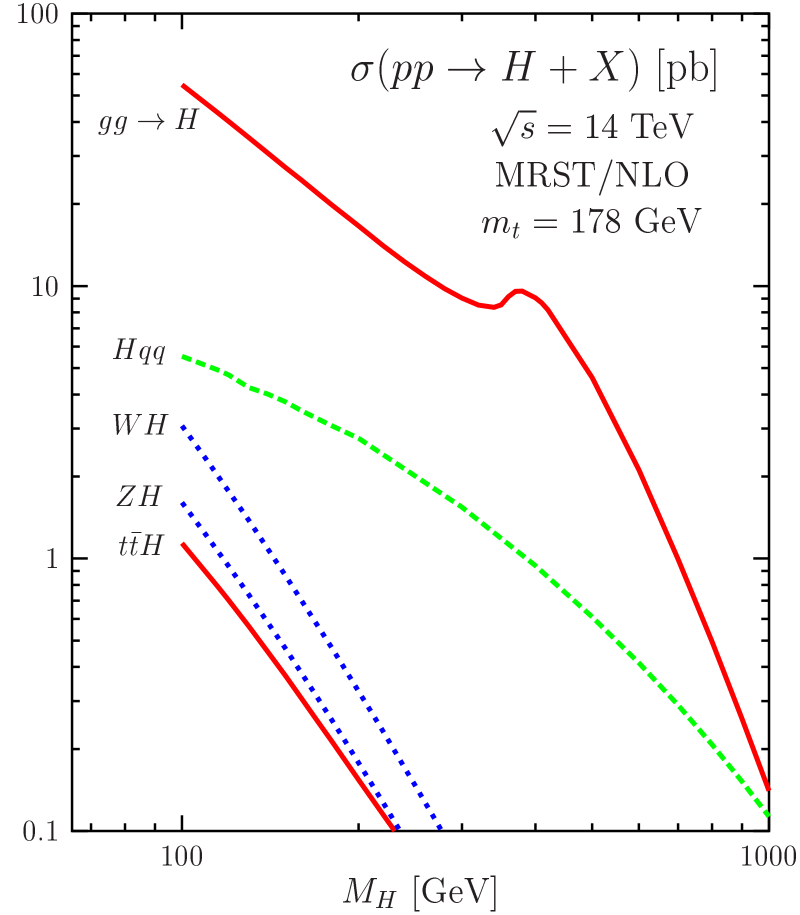




- Large corrections from extensions of Standard Model
  - t-channel: anomalous couplings or flavor changing neutral currents
  - s-channel: charged “top-pion”, Kaluza-Klein modes of W or W‘-boson

Higgs production at LHC

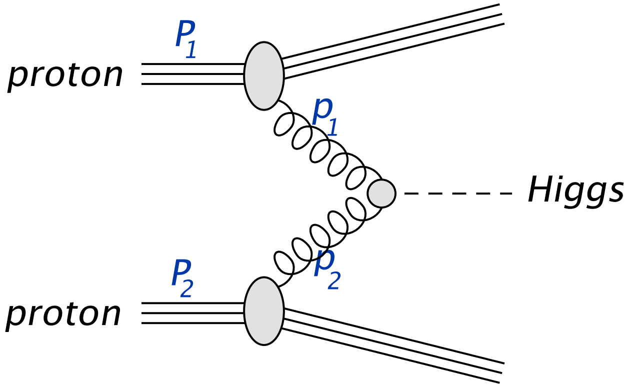


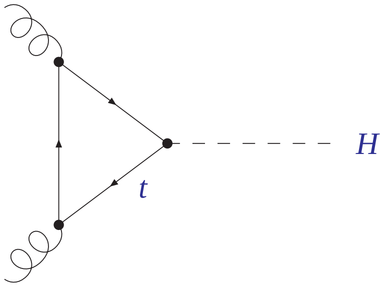


- Standard model Higgs
  - branching ratios for decay (left) and dominant production modes (right)
    Djouadi '05

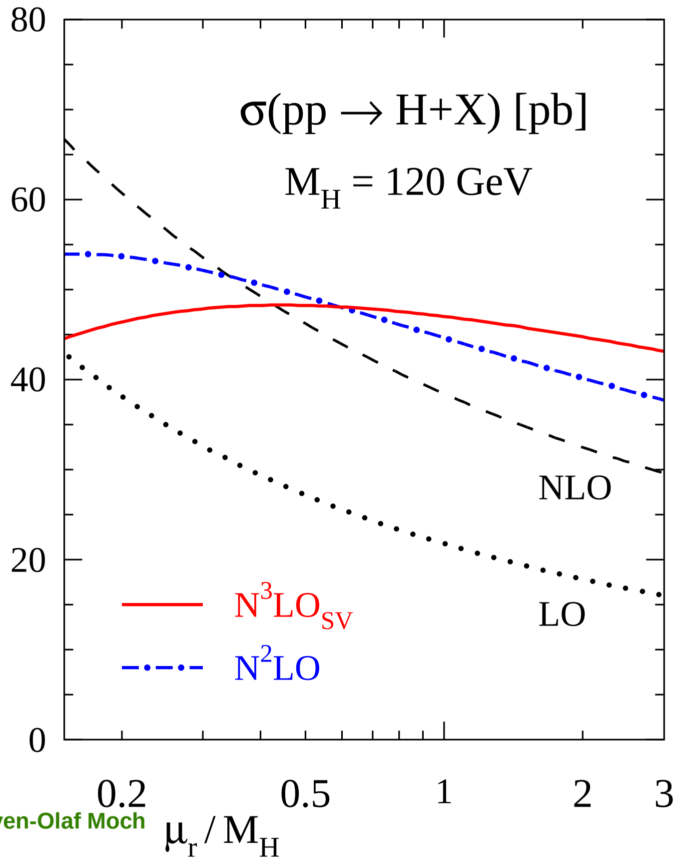
Gluon fusion

- Largest rate for all values of Higgs mass M_H (top-Yukawa coupling)





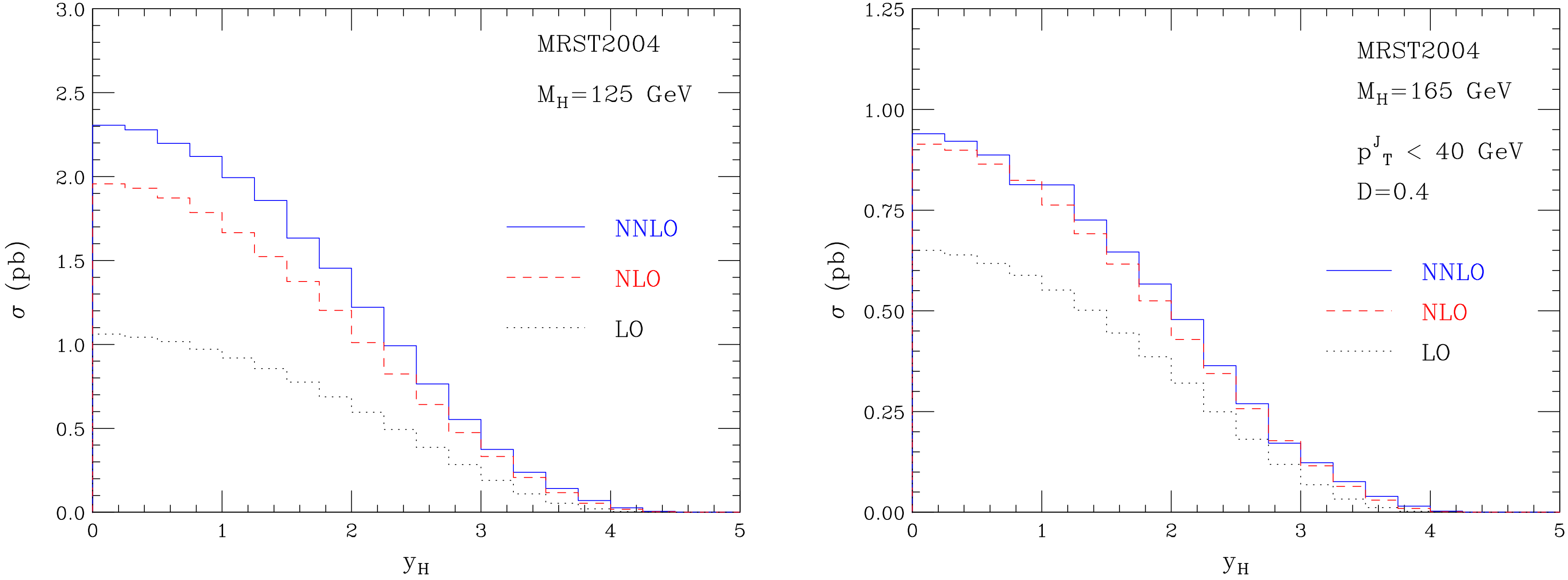
heavy top limit $m_t \to \infty$:
effective gg Higgs vertex



- Total cross section with QCD corrections
- Variation of renormalization scale for Higgs mass $M_H = 120$GeV
  - NNLO corrections
    Harlander, Kilgore '02; Anastasiou, Melnikov '02; Ravindran, Smith, van Neerven '03
  - complete soft N^3LO corrections
    S.M., Vogt '05

Differential distributions in gluon fusion

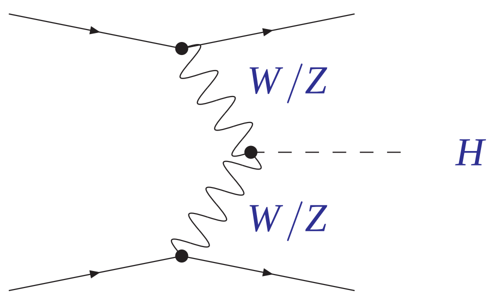
- Bin-integrated Higgs rapidity distribution including decay $H \to \gamma\gamma$
  - QCD corrections up to NNLO Anastasiou, Melnikov, Petriello ‘05
  - fast parton level Monte Carlo HNNLO Catani, Grazzini ‘07

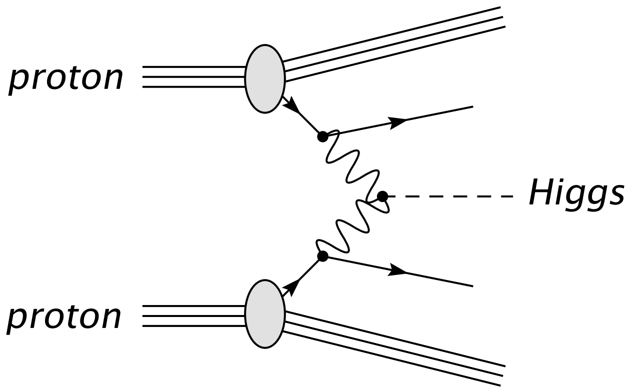


- Impact of kinematical cuts on higher order corrections
  - left: Higgs mass $M_h = 125$ GeV, no cuts on p_t of jets
  - right: Higgs mass $M_h = 165$ GeV and veto on jets with $p_t > 40$ GeV (k_t algorithm for jet reconstruction with jet size $D = 0.4$)

Weak vector-boson fusion

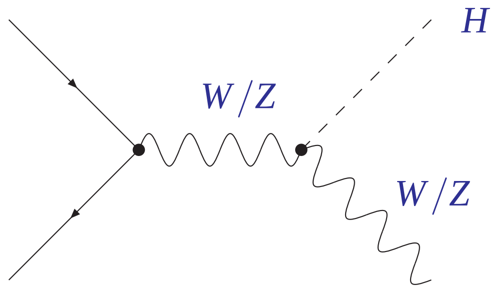
- Channel $qq \to qqH$ (with cuts on jets energies)
- Second largest rate (WWH coupling)
  - mostly dominated by u, d-quarks





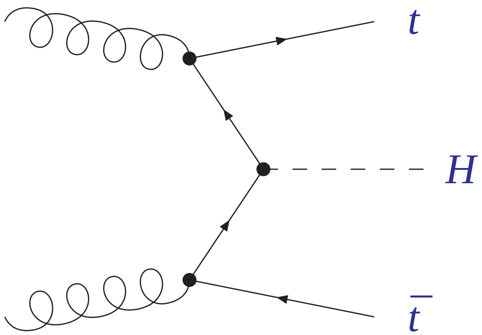
Higgs-strahlung

- Channel $q\bar{q} \to W(Z)H$
- Third largest rate (same couplings as vector boson fusion)



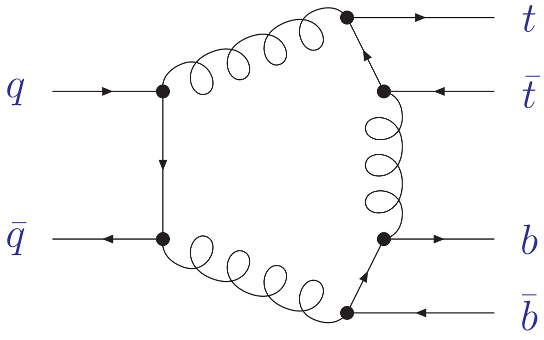
$t\bar{t}$H

- Channel $pp \to t\bar{t}H$
  - discovery channel in low mass region $M_H \lesssim 130$ GeV
  - driven by gluon luminosity, but large SM background $pp \to t\bar{t}H \to t\bar{t}b\bar{b}$



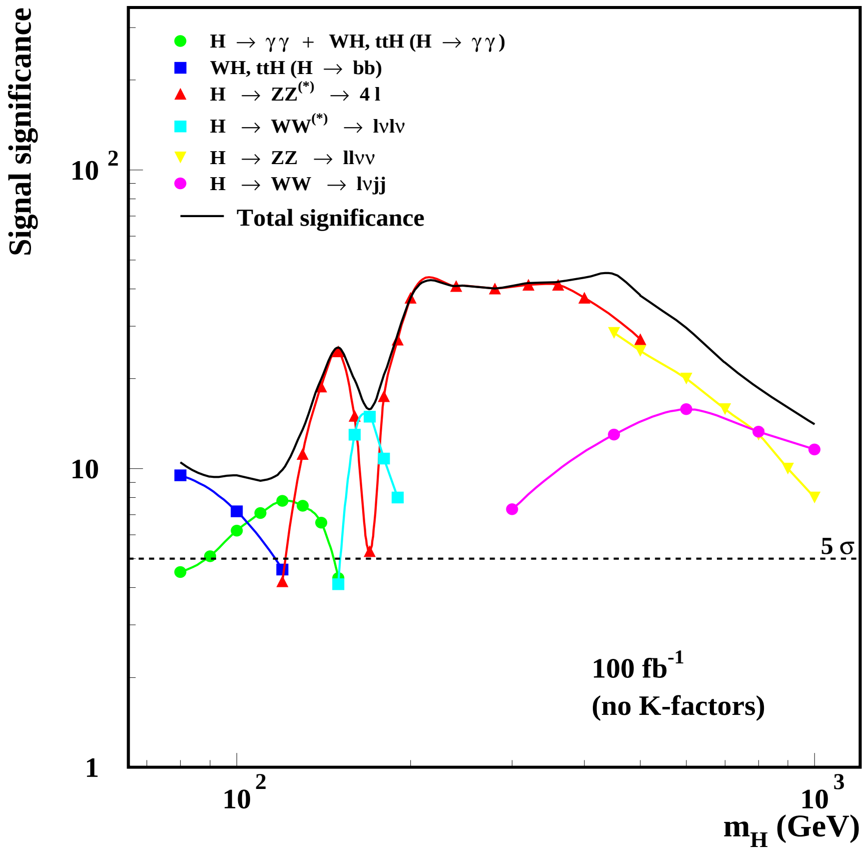
- Main backgrounds for $pp \to t\bar{t}H$
  - combinatorial background from signal (4 b-quarks in final state)
  - $t\bar{t} + 2$ jets, $t\bar{t}b\bar{b}$, $t\bar{t}Z$
  - complex final states

- **New**: NLO QCD corrections to $q\bar{q} \to t\bar{t}b\bar{b}$
  Denner, Dittmaier, Pozzorini '08
  - extremely diffcult hexagon integrals with masses



Progress in theory

- Sensitivity for Higgs production at LHC
  - inclusion of higher order theory predictions in new studies
  - e.g. $pp \to t\bar{t}H$ absent in CMS plot



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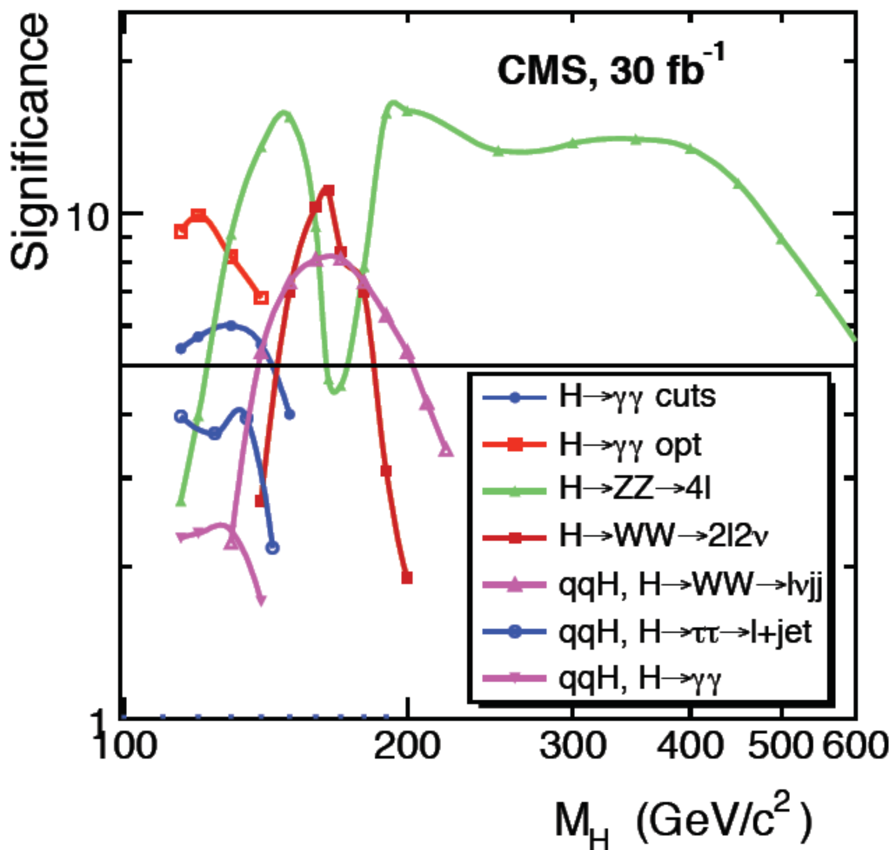

2006

Summary

Hard QCD

- Parton luminosity at hadron colliders
- Hard parton cross section
  - $W^{\pm}/Z$-boson production
  - jet cross sections
  - hadro-production of top quarks
  - Higgs total cross section
- Hadronic final state
  - jet algorithms and fragmentation of (heavy) quarks
  - parton shower Monte Carlo simulation

Outlook

- QCD tool box ready for LHC challenges
  - however, still much dedicated work to do