Theoretical predictions for the LHC

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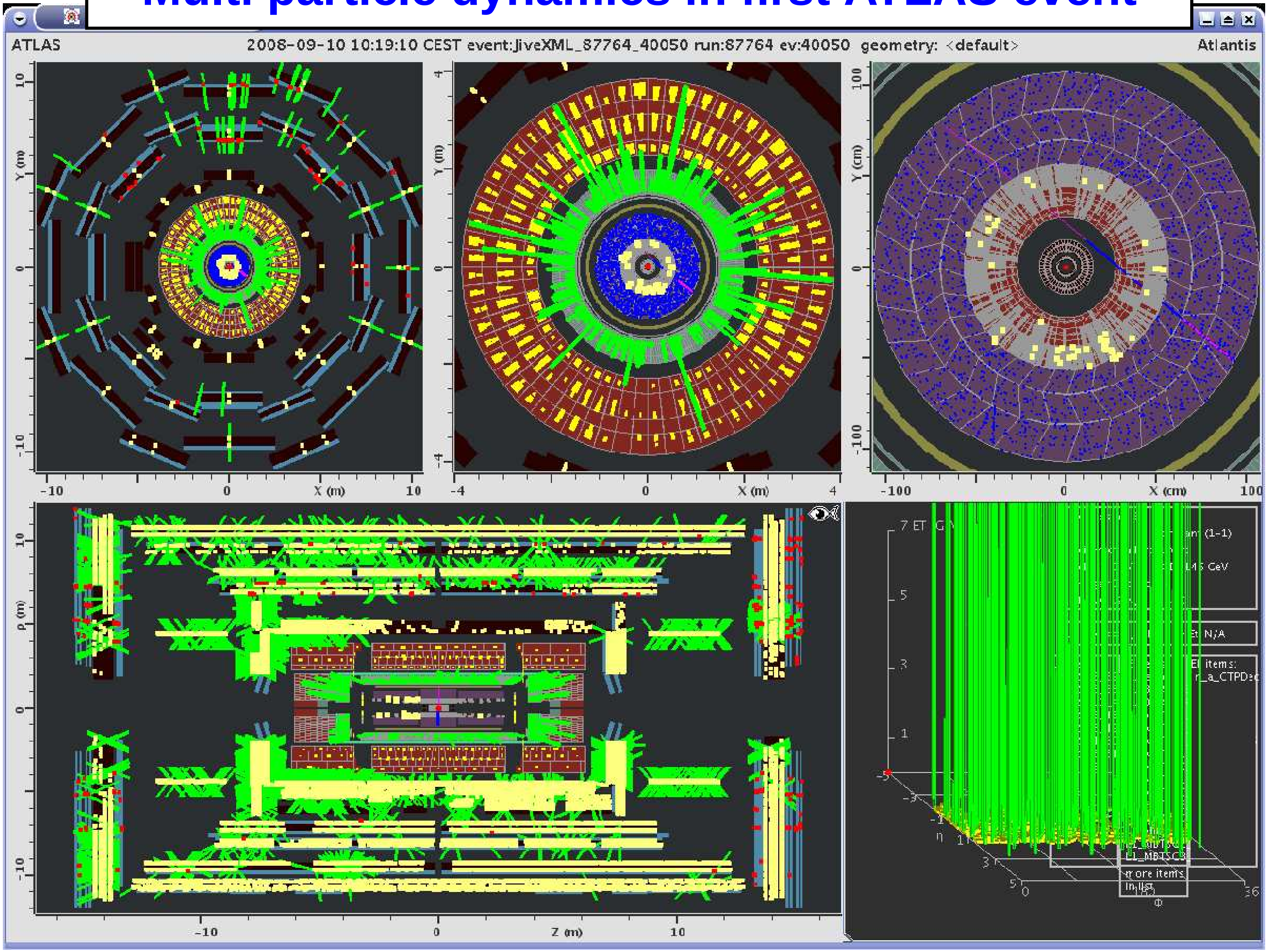
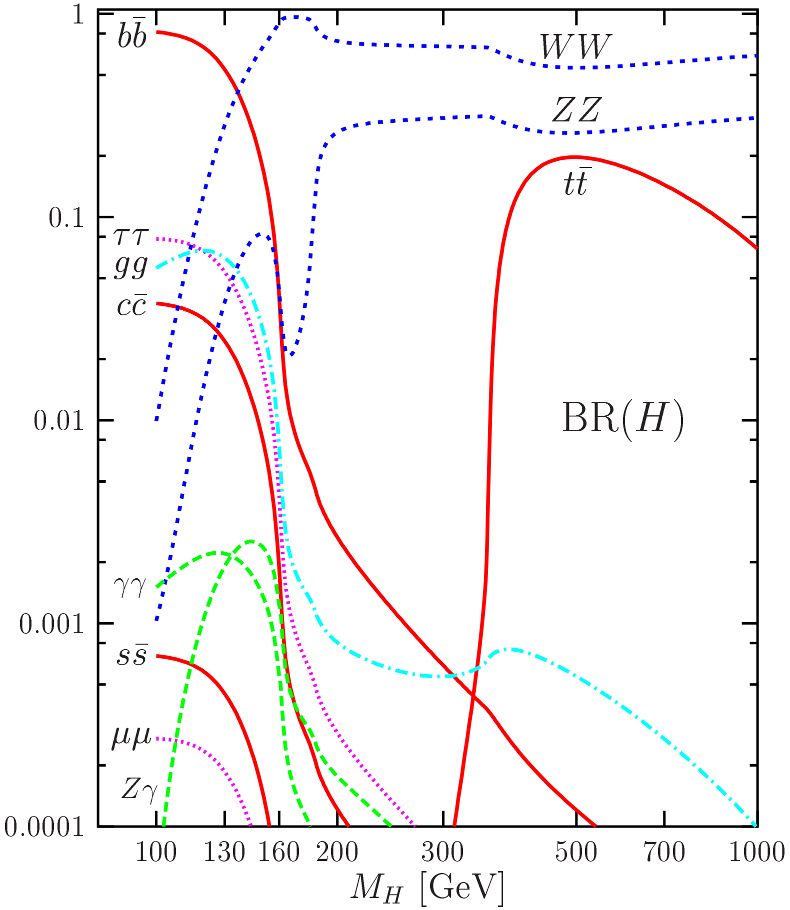
Multi particle dynamics in first ATLAS event

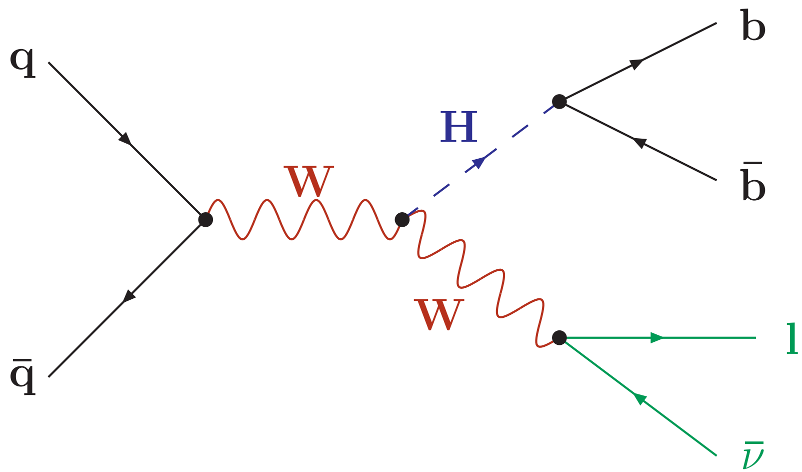


Higgs production at LHC



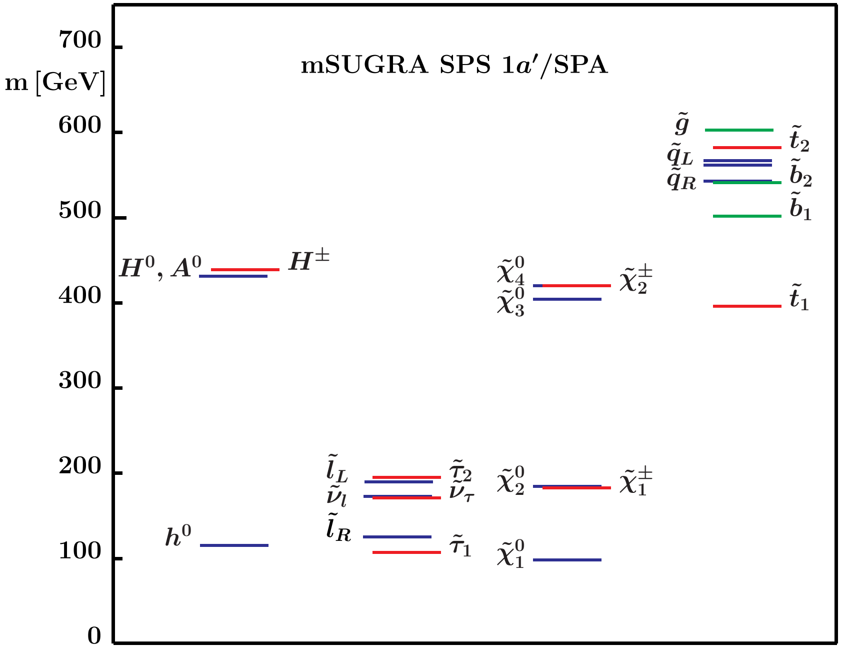
- Branching ratios for decay of Standard Model Higgs

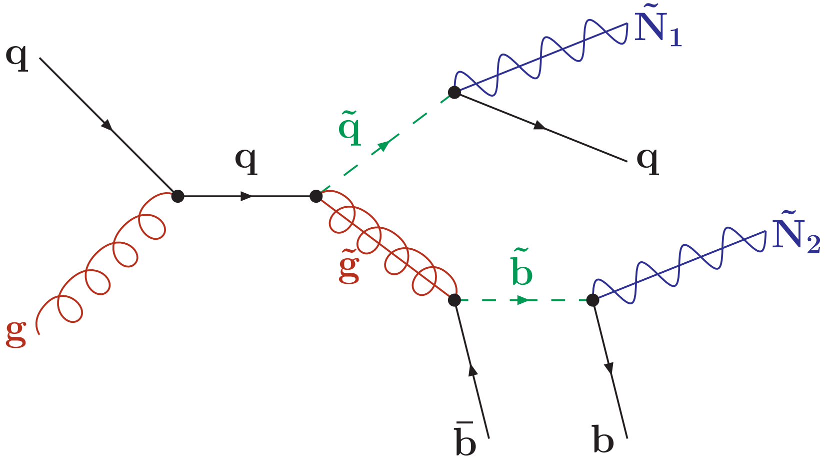
- High-multiplicity final states
  - typical SM process is accompanied by radiation of multiple jets
- Example: Higgs-strahlung
  - channel $q\bar{q} \to W(Z)H$ (third largest rate at LHC)
  - dominant decay $H \to b\bar{b}$



Supersymmetry

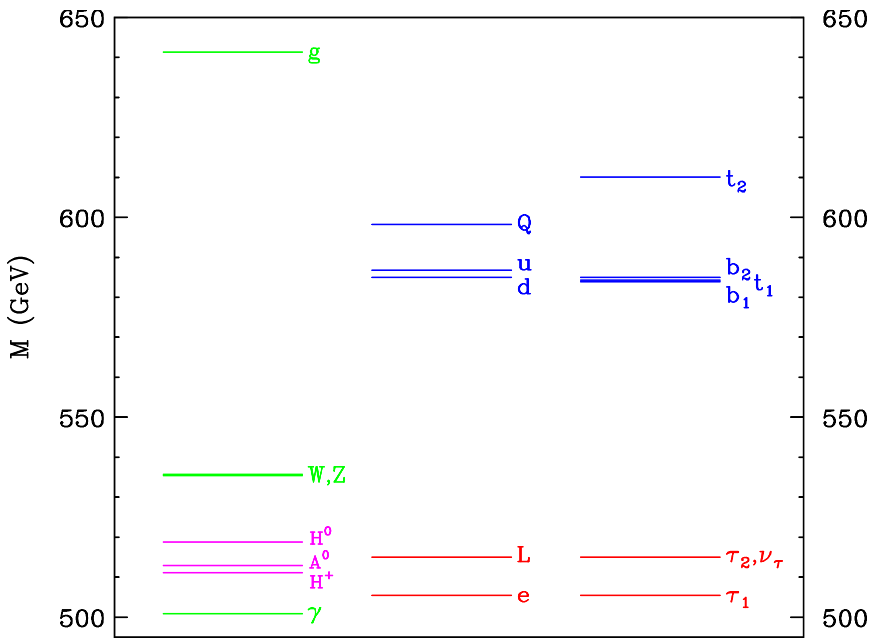
- Pair-production of supersymmetric particles (R-parity)
  - lightest supersymmetric particle (LSP) must be absolutely stable
- MSSM spectrum
  - typical signature: multiple jets, leptons and missing energy
- Example: neutralino production $\tilde{N}^0_{1,2}$
  - electric and color-neutral (dark matter candidate)

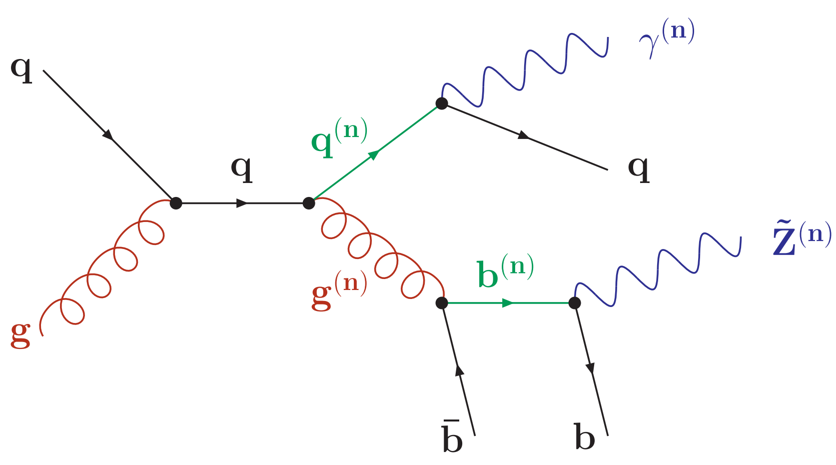




Large extra dimensions

- Spectrum of first Kaluza-Klein excitations
  - effective mass $\simeq$ (compactification radius)$^{-1}$, $m^{(n)} \simeq 1/R$
- Pair-production of excited KK-modes in interactions
  - phenomenology: missing energy in subsequent chain decays





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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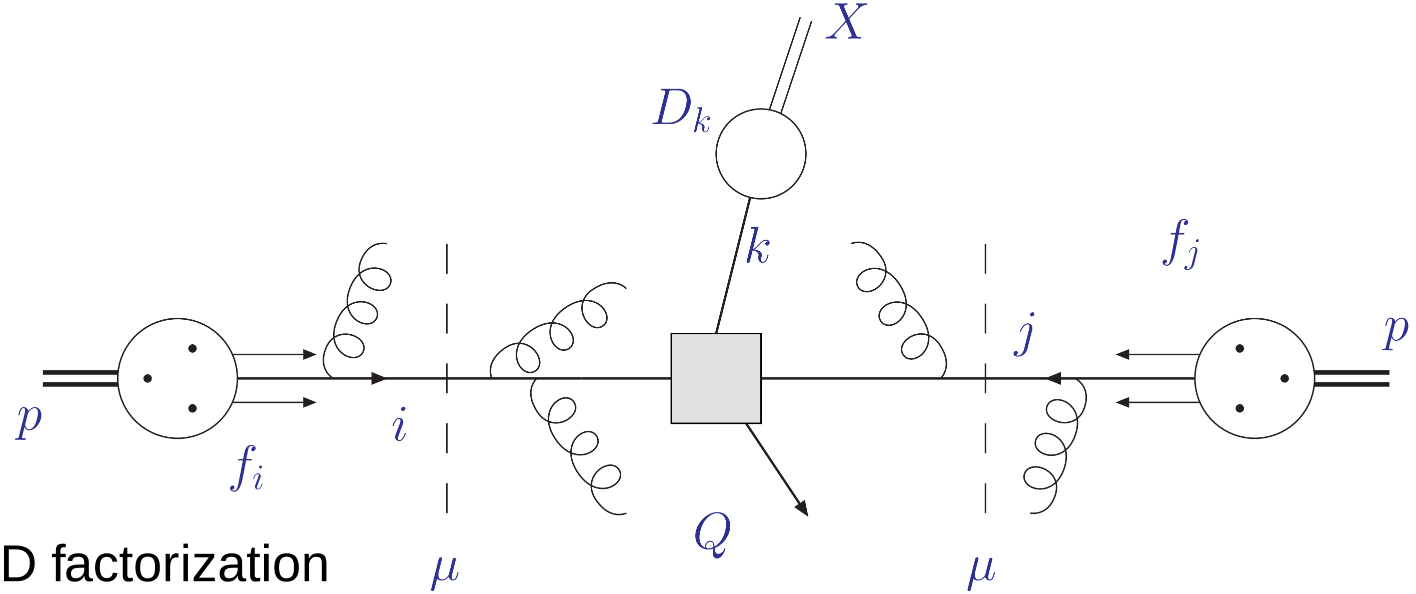
Tools

- 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

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

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

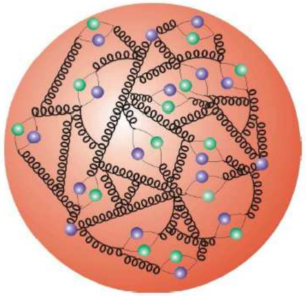
  - factorization scale μ, subprocess cross section $\hat{\sigma}_{ij\to k}$ for parton types i, j and hadronic final state X

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



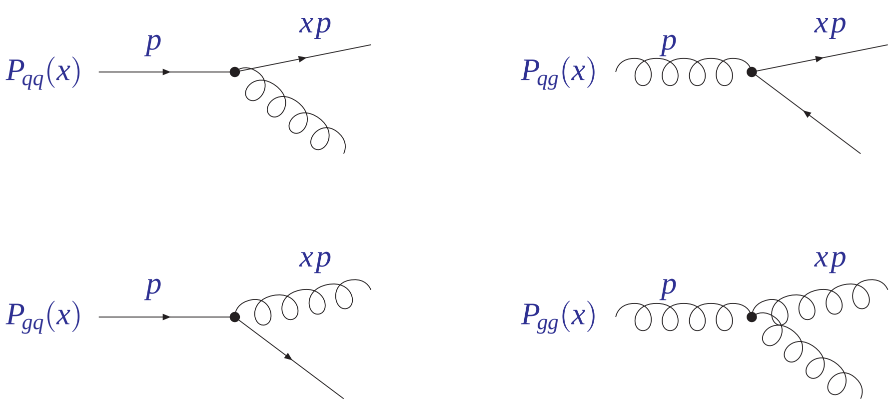
- Final state X: hadrons, mesons, jets, . . .
  - fragmentation function $D_{k\to X}(\mu^2)$ or jet algorithm
  - interface with showering algorithms (Monte Carlo)

Parton distributions in proton

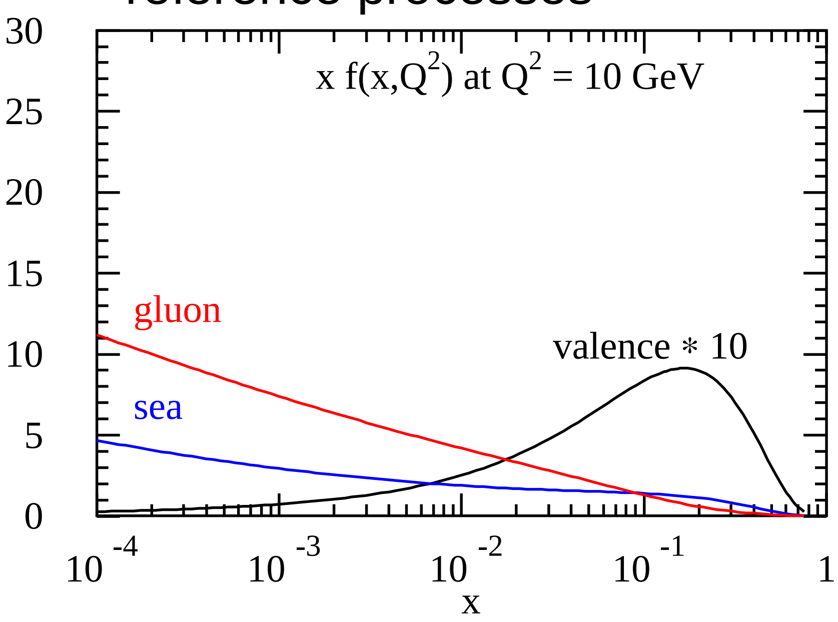
- Evolution equations for parton distributions f_i
  - splitting functions $P = \alpha_s P^{(0)} + \alpha_s^2 P^{(1)} + \alpha_s^3 P^{(2)} + \ldots$
    (calculable in perturbative QCD)

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

parton splitting in leading order



universality: predictions from fits to reference processes



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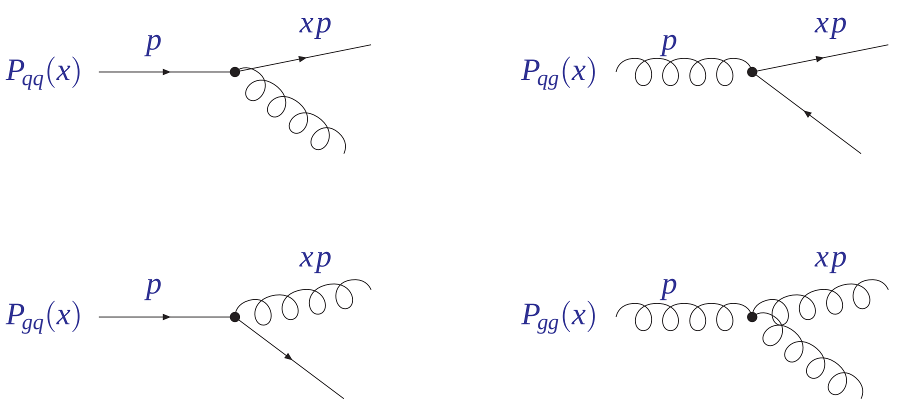

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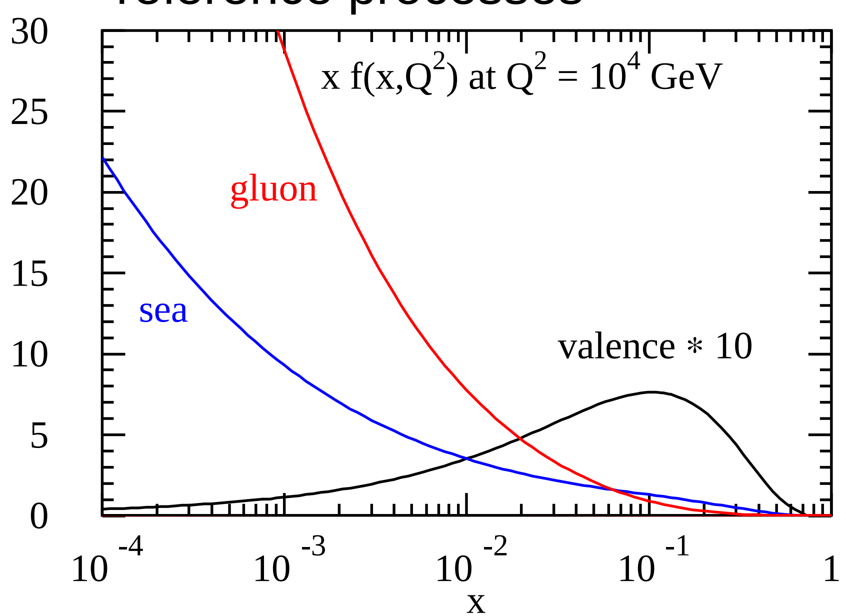
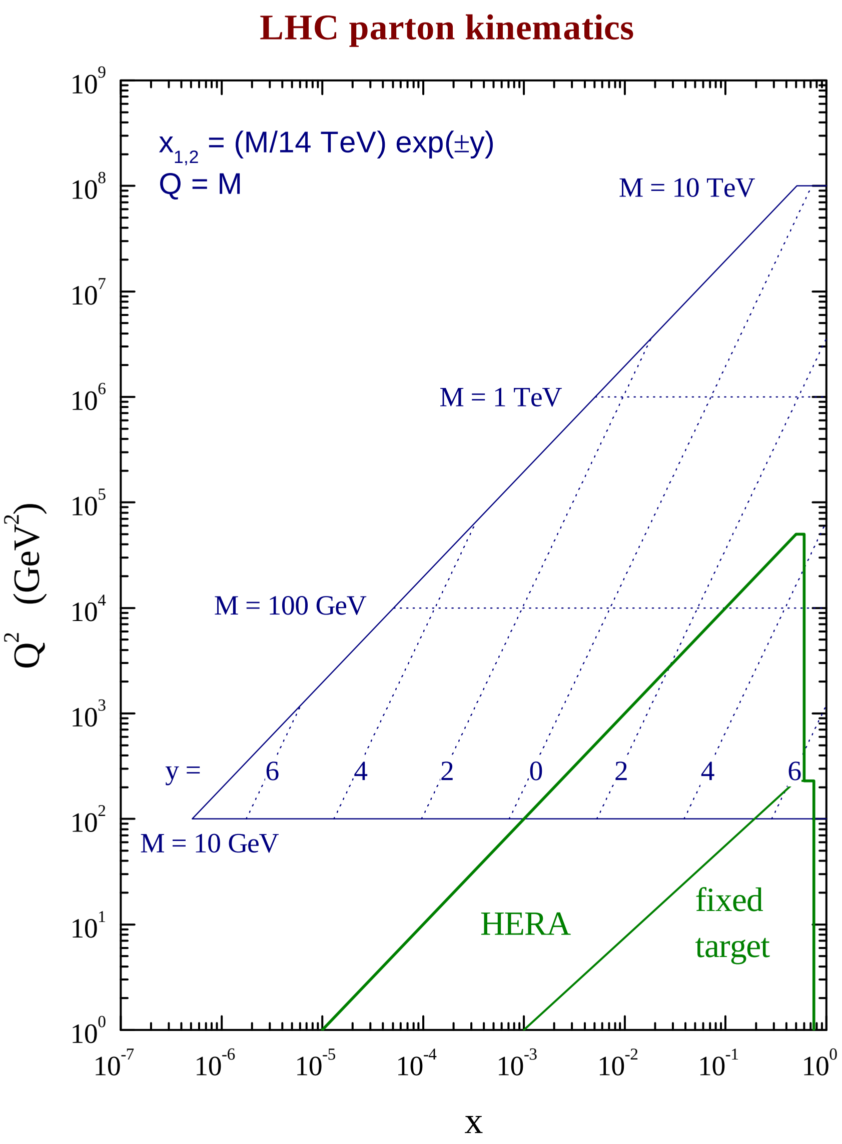


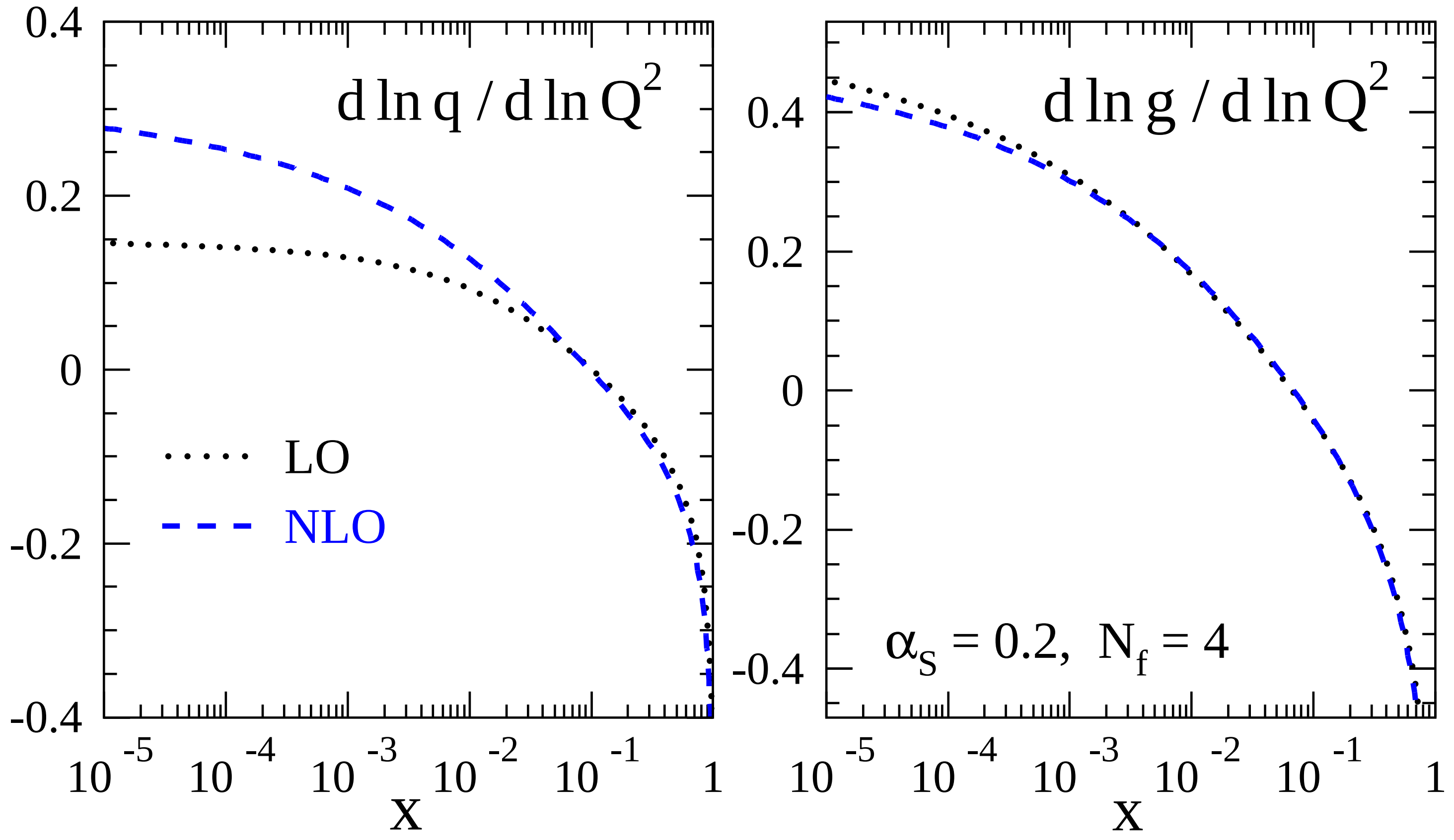
Parton luminosity at LHC

- Precision HERA data on F_2 covers most of the LHC x-range
- Scale evolution of PDFs in Q over two to three orders
- Sensitivity at LHC
  - 100 GeV physics: small-x, sea partons
  - TeV scales: large-x
  - rapidity distributions probe extreme x-values
- Stable evolution in QCD
  - splitting functions to NNLO
    S.M. Vermaseren, Vogt '04



Perturbative stability of evolution

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



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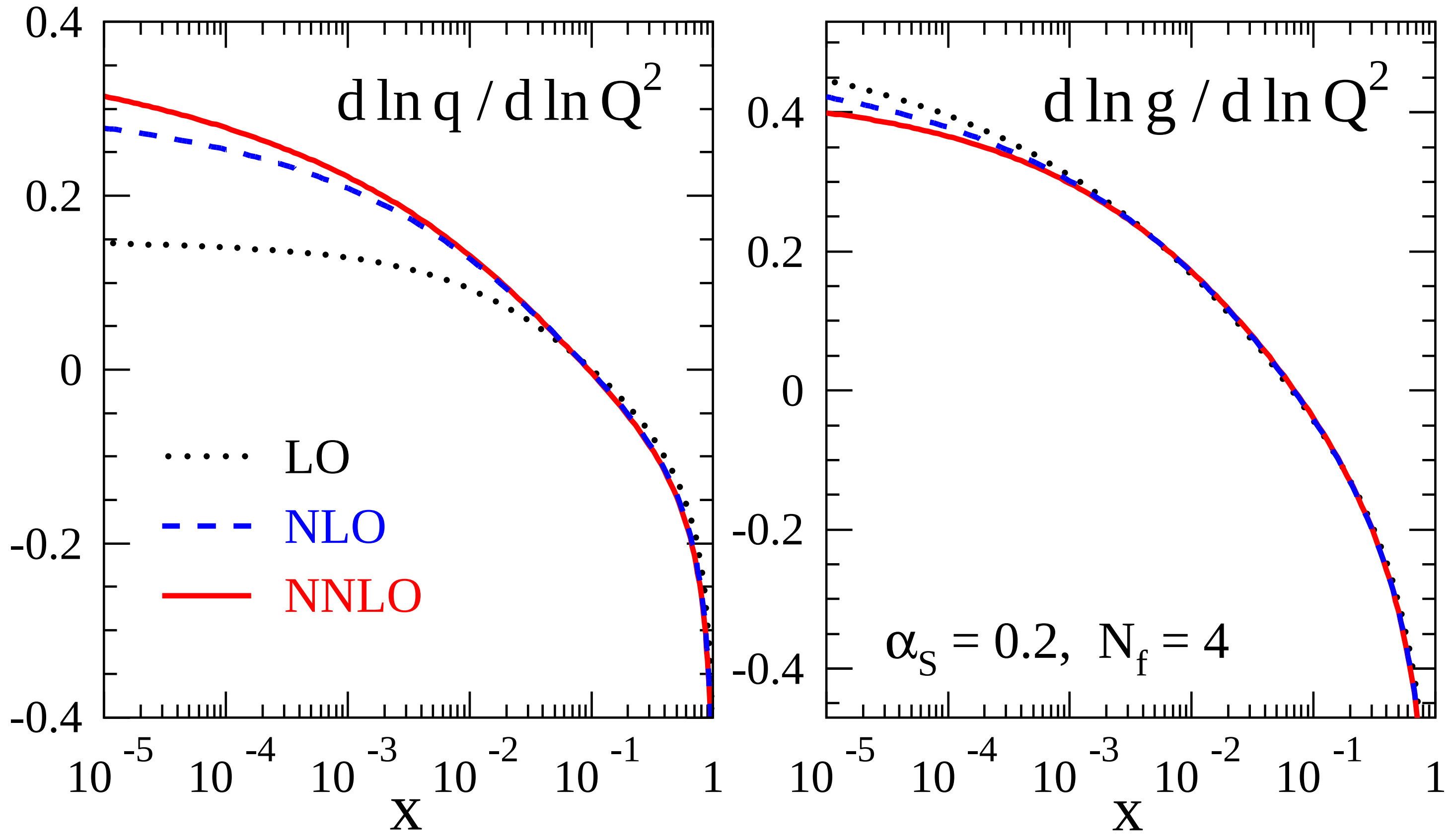
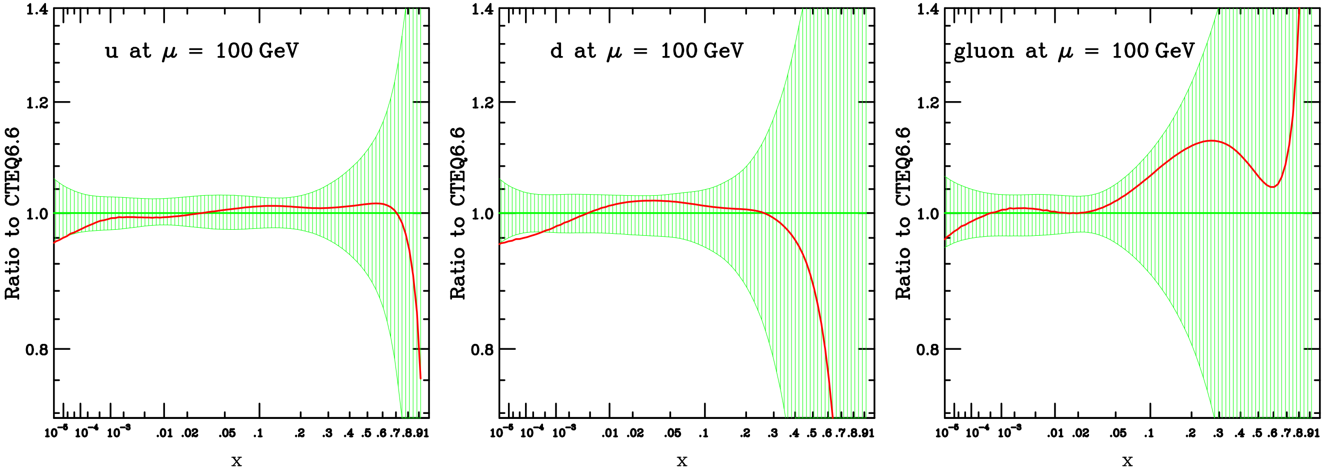


- Expansion very stable except for very small momenta $x \lesssim 10^{-4}$
  S.M. Vermaseren, Vogt '04

Status of PDFs

- Public codes for NNLO DGLAP evolution of PDFs PEGASUS Vogt '04; QCDNUM Botje '07; CANDIA Cafarella et al. '08; HOPPET Salam, Rojo '08
- Continuous updates of global fits Alekhin, CTEQ, MSTW collaborations
  - improved treatment of heavy quark (charm) threshold
  - systematic use of uncertainties/correlations
- New experimental data
  - neutrino-nucleon DIS for strange quark PDFs ($s \neq \bar{s}$)
  - HERA jets, Tevatron high-E_T jets (high-x gluon)
  - Tevatron lepton-asymmetry (u, d flavor separation)
  - ...



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  - . . .

Outlook

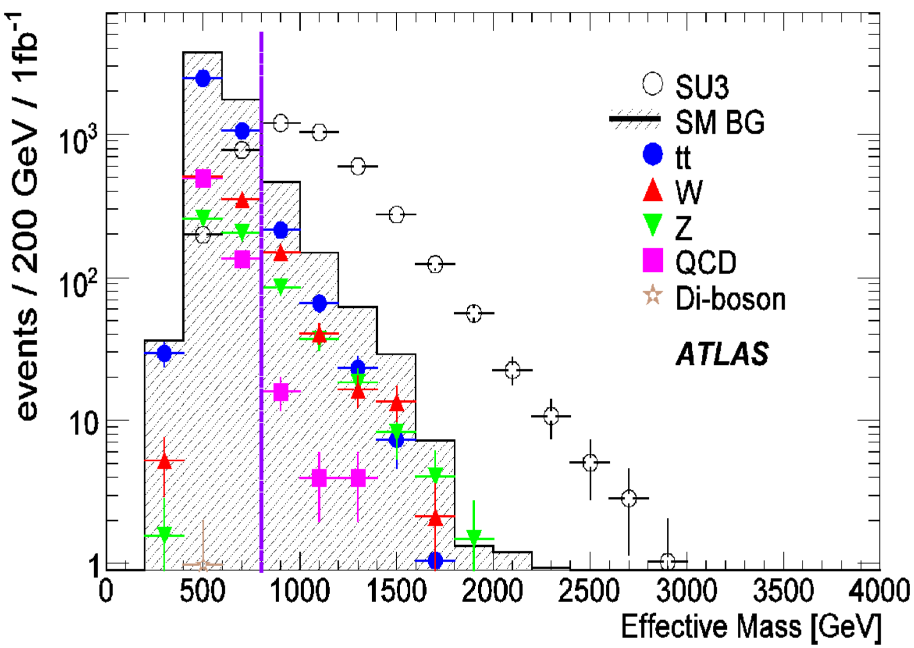
- PDFs are precision physics
  - determination of PDFs from LHC data requires very good control of experimental systematics, e.g. jet measurements, . . .

Parton cross sections

Accuracy of perturbative predictions for 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^3LO (next-to-next-to-next-to-leading order)
  - very few ...

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, $\tan\ \beta = 6, A_0 = -300, \mu > 0$

- SM background in high-end tail of missing E_T
- SM processes at LO with large uncertainty
  - 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 $\Delta(\sigma^{\mathrm{LO}}) \simeq 40\%$
- Significance of potential disagreement between data and MadGraph/Sherpa/Algen/... ?

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, but no general libraries available
- **Speed and stability** are the important criteria in practice

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  Virtual corrections
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Recent progress

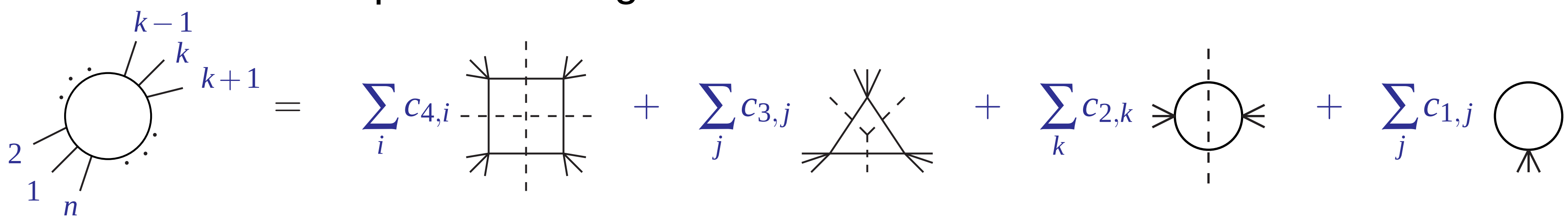
- Cancelation of divergences: automated subtraction Gleisberg, Krauss '07; Seymour, Tevlin '08; S.M., Hasegawa, Uwer '08; Gehrmann, Greiner, Frederix '08
- Virtual corrections: automated computation of n-point amplitudes Ellis, Giele, Kunszt, Melnikov '08; Giele, Zanderighi '08; Berger, Bern, Cordero, Dixon, Forde, Ita, Kosower, Maitre '08

NLO virtual amplitudes

- Straightforward in principle – hard in practice with known bottlenecks
  - one-loop tensor integrals (standard Passarino-Veltman reduction)

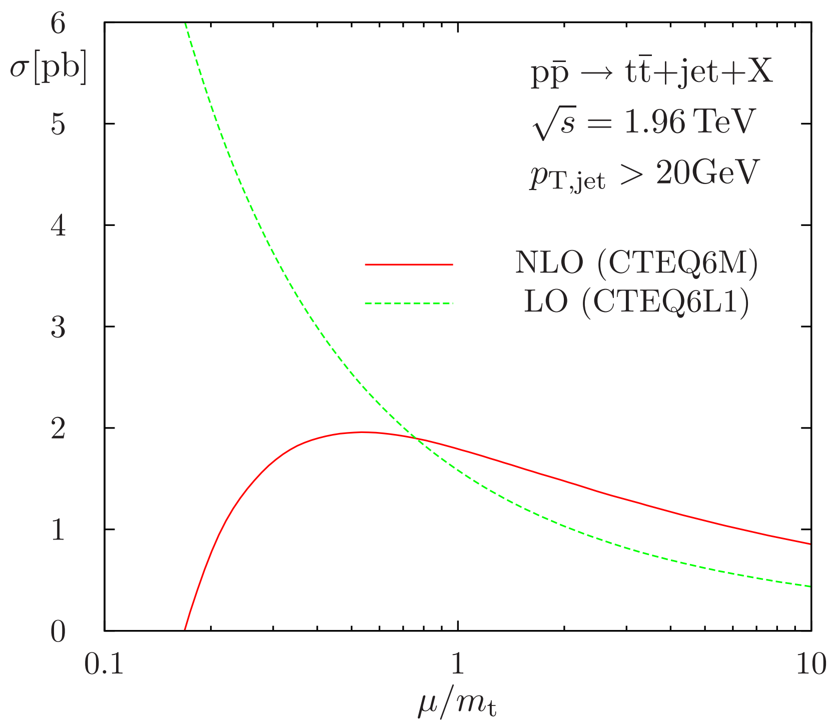
$$I^{\mu_1,\mu_2,\dots}(k_1,\dots) = \int d^D p_1 \frac{p_1^{\mu_1} p_2^{\mu_2} \dots}{(p_1^2 - m_1^2)((p_1 - k_1)^2 - m_2^2)\ \dots}$$

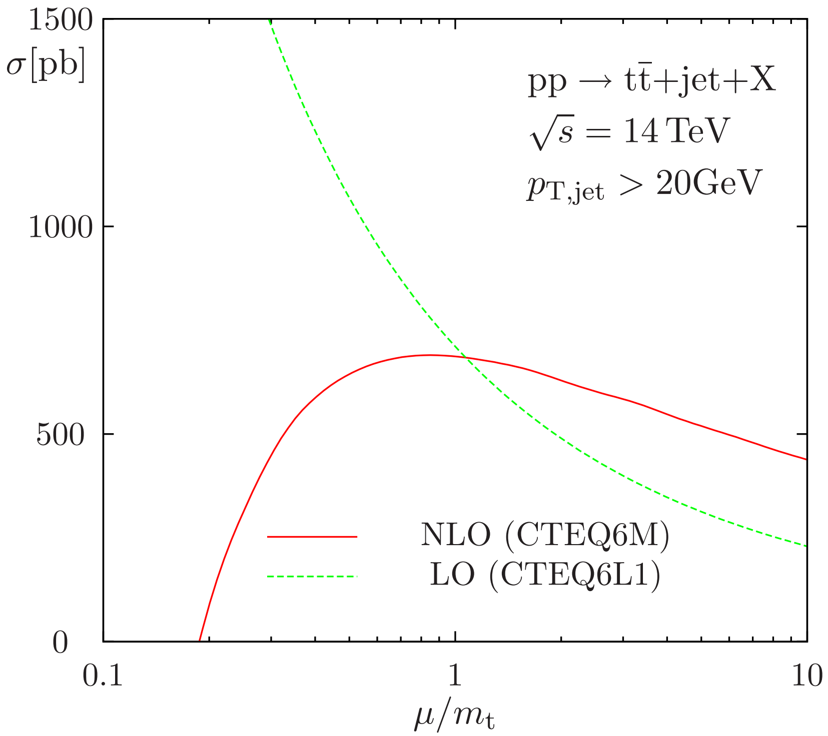
- **New** recursive on-shell approach Bern, Dixon, Dunbar, Kosower ‘94; Britto, Cachazo, Feng ‘04; Ossola, Pittau, Papadopolous ‘06, . . .
  - sew tree level amplitudes together (on-shell with complex momenta)
  - algebraic extraction of coefficients of 4-, 3- , 2- and 1-point one-loop scalar integrals



- Use also **well-known** methods
  - colour ordering; helicity amplitudes; supersymmetry; factorization properties of amplitudes

Example of NLO calculation: $t\bar{t}+$ jet production





- Impressive state-of-the-art NLO QCD calculation
  Dittmaier, Uwer, Weinzierl '07
- Much improved scale dependence at NLO
  - essential ingredient of NNLO $t\bar{t}$-production
- Effect on A_{FB} at Tevatron large: now compatible with zero

Complete NLO results

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

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

  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

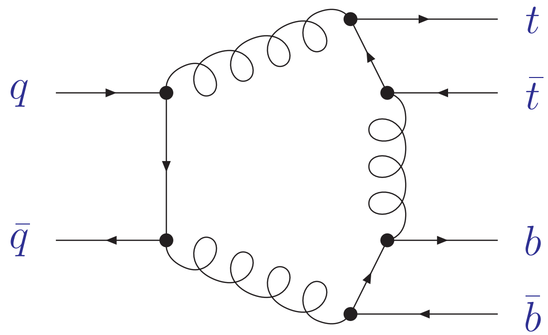
  - $pp \to t\bar{t} + \text{jet}$ at NLO Dittmaier, Uwer, Weinzierl '07
    $pp \to WW + \text{jet}$ at NLO Dittmaier, Kallweit, Uwer '07; Campbell, Ellis, Zanderighi '07
    $pp \to ZZZ$ at NLO Lazopoulos, Melnikov, Petriello '07
    $pp \to WWZ$ at NLO Hankele, Zeppenfeld '07

- Full automation for NLO cross sections for $2 \to 3$ processes
  $\longrightarrow$ still to lift off ground

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

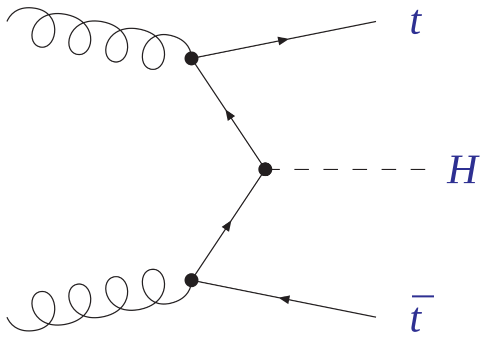
Irreducible background

- **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



Signal

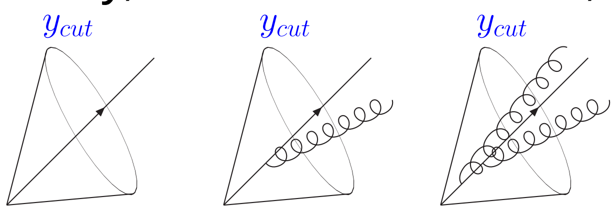
- Channel $pp \to t\bar{t}H$
  - discovery channel in low mass region $M_H \lesssim 130$ GeV
  - driven by gluon luminosity, but large SM background $pp \to t\bar{t}H \to t\bar{t}b\bar{b}$



- 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)

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, ...

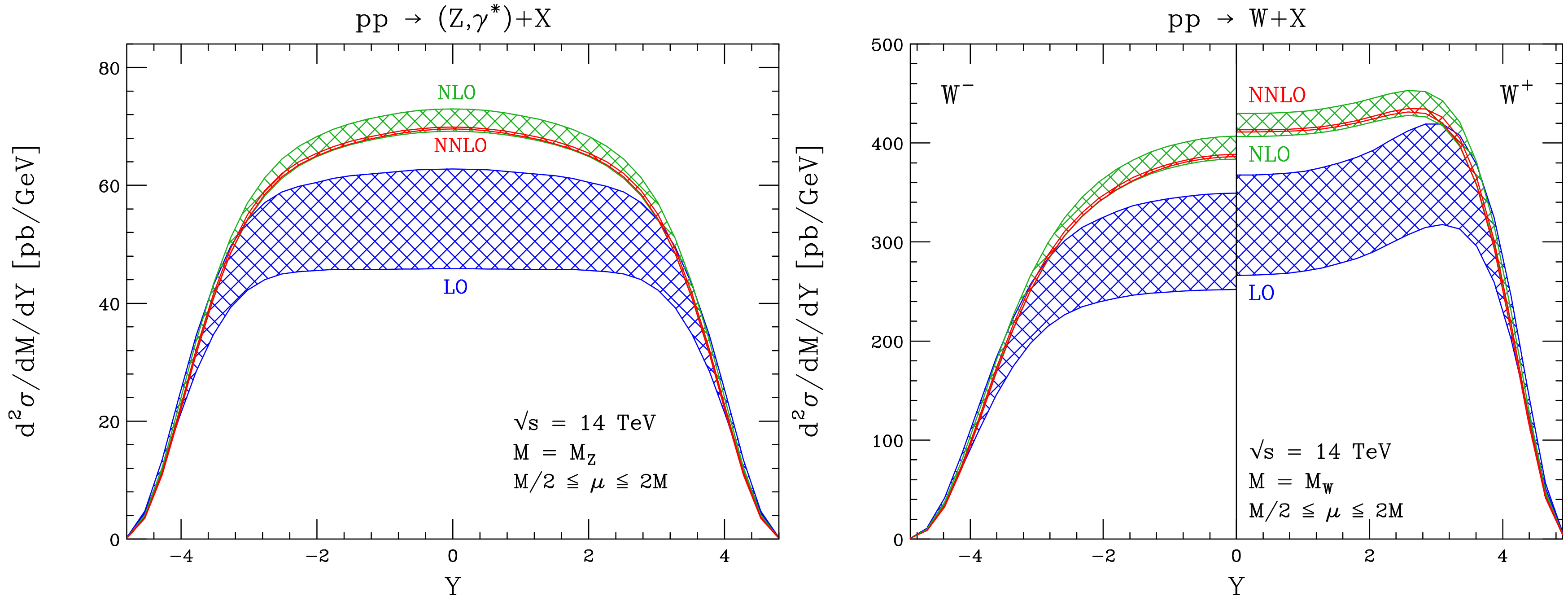


- Calculation of NNLO cross sections
  - cancellation of infrared divergencies highly non-trivial
  - (two-loop) virtual amplitudes
    Anastasiou, Bern, v.d.Bij, De Freitas, Dixon, Ghinculov, Glover, Oleari, Schmidt, Tejeda-Yeomans, Wong ‘01-‘04 and Garland, Gehrmann, Glover, Koukoutsakis, Remiddi, ‘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; Weinzierl ‘08

Gauge boson production at NNLO

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

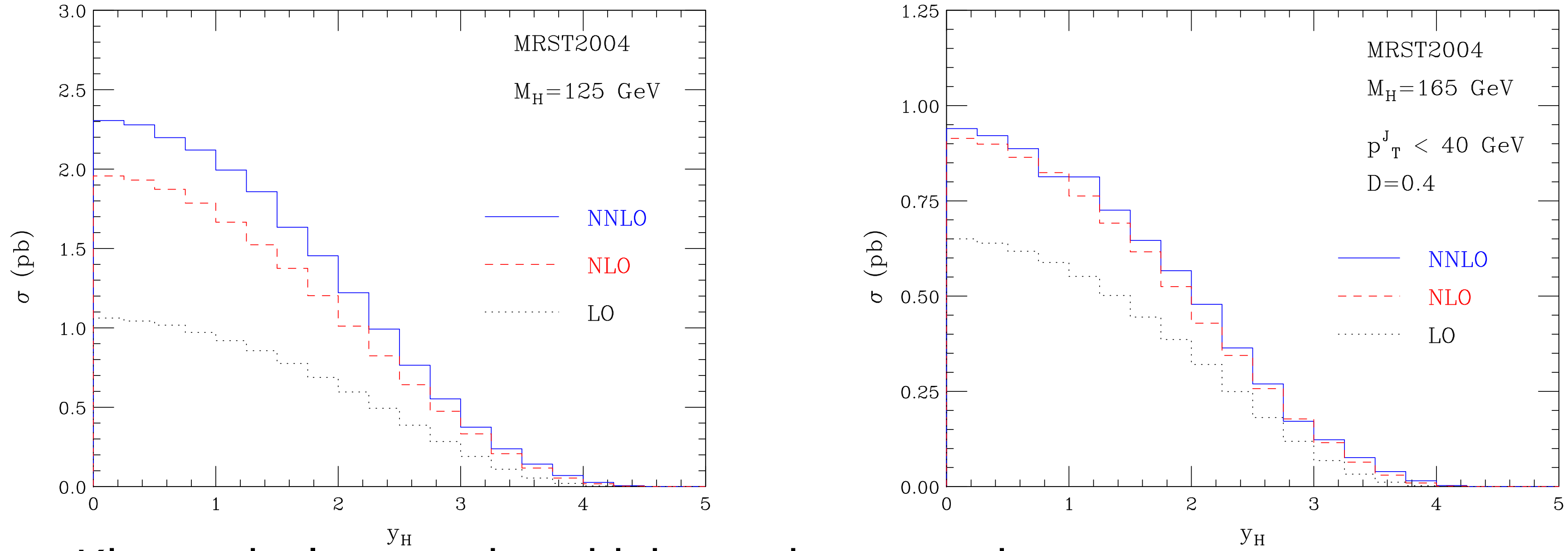
  Anastasiou, Petriello, Melnikov '05



- NNLO QCD theoretical uncertainties (renormalization / factorization scale) at level of 1% Dissertori et al. '05
- "Standard candle" process for parton luminosity
  - large statistics even in early LHC data

Higgs production in gluon fusion at NNLO

- Bin-integrated Higgs rapidity distribution including decay $H \to \gamma\gamma$
  - QCD corrections up to NNLO Anastasiou, Melnikov, Petriello '05; Catani, Grazzini '07



- Kinematical cuts reduce 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 $D = 0.4$)
- Soft gluon resummation reduces scale dependence
  - complete N^{3}LO soft corrections S.M., Vogt '05

Top-quark pair-production

- NLO (plain vanilla) QCD corrections known since long
  Nason, Dawson, Ellis '88; Beenakker, Smith, van Neerven '89; Mangano, Nason, Ridolfi '92; Bernreuther, Brandenburg, Si, Uwer '04; . . .

Kinematical limits

- Exact results partially available
  - full mass dependence for two-loop virtual $\mathrm{q\bar{q}} \to \mathrm{t\bar{t}}$ Czakon '08
  - analytic two-loop fermionic corrections for $\mathrm{q\bar{q}} \to \mathrm{t\bar{t}}$ Bonciani, Ferroglia, Gehrmann, Maitre, Studerus '08
- Small-mass limit $m^2 \ll s, t, u$ for two-loop virtual corrections to $\mathrm{q\bar{q}} \to \mathrm{t\bar{t}}$ and $\mathrm{gg} \to \mathrm{t\bar{t}}$ S.M., Czakon, Mitov '07
  - based on simple multiplicative relation between massive $\mathcal{M}^{(m)}$ and massless $\mathcal{M}^{(m=0)}$ amplitudes to all orders S.M., Mitov '06
- Threshold at $s \simeq 4m^2$
  - parton cross section exhibit Sudakov-type logarithms $\ln(\beta)$ with velocity of heavy quark $\beta = \sqrt{1 - 4m^2/s}$ (Sudakov resummation)

$$\alpha_s^n \ln^{2n}(\beta) \longleftrightarrow \alpha_s^n \ln^{2n}(N)$$

Results

- NNLO cross section for heavy-quark hadro-production near threshold (all powers of $\ln\beta$ and Coulomb corrections) S.M., Uwer '08
    - e.g. gg-fusion for $n_f = 5$ light flavors at $\mu = m$

$$\hat{\sigma}^{(1)}_{gg\to t\bar{t}} = \hat{\sigma}^{(0)}_{gg\to t\bar{t}}\left\{96\ln^2\beta - 9.5165\ln\beta + 35.322 + 5.1698\frac{1}{\beta}\right\}$$

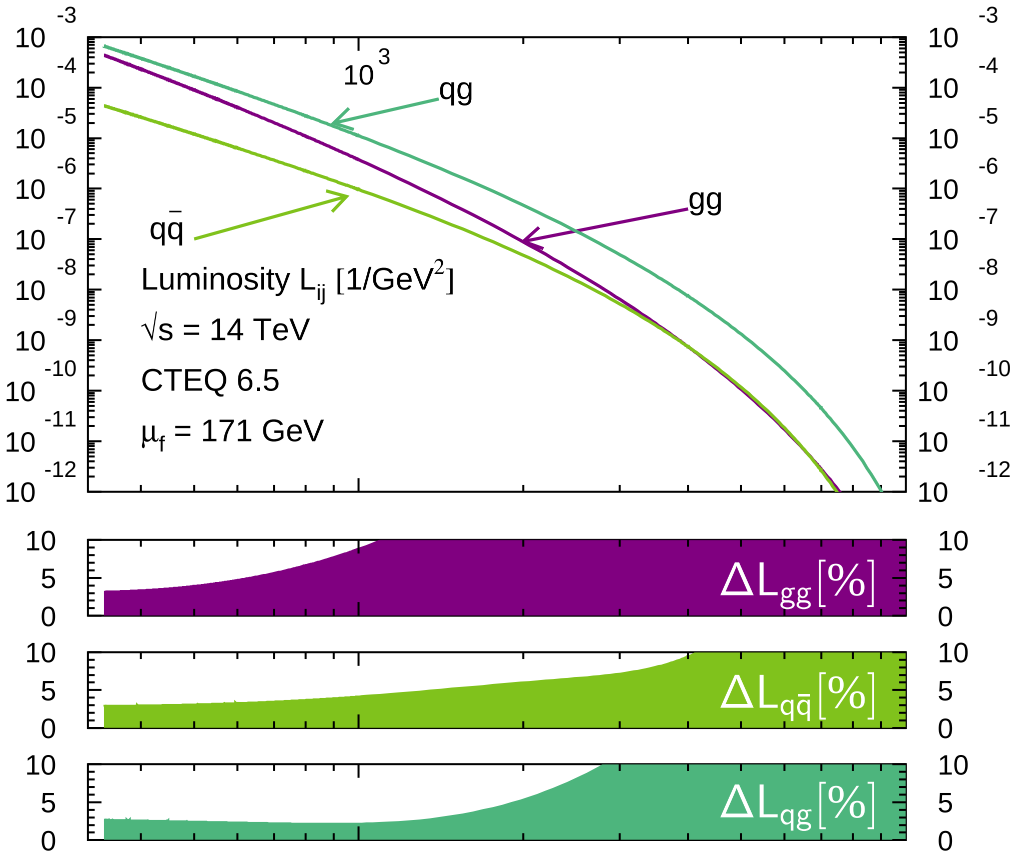
$$\hat{\sigma}^{(2)}_{gg\to t\bar{t}} = \hat{\sigma}^{(0)}_{gg\to t\bar{t}}\left\{4608\ln^4\beta - 1894.9\ln^3\beta + \left(-3.4811 + 496.30\frac{1}{\beta}\right)\ln^2\beta \right.$$
$$\left. + \left(3144.4 + 321.17\frac{1}{\beta}\right)\ln\beta + 68.547\frac{1}{\beta^2} - 196.93\frac{1}{\beta} + C^{(2)}_{gg}\right\}$$

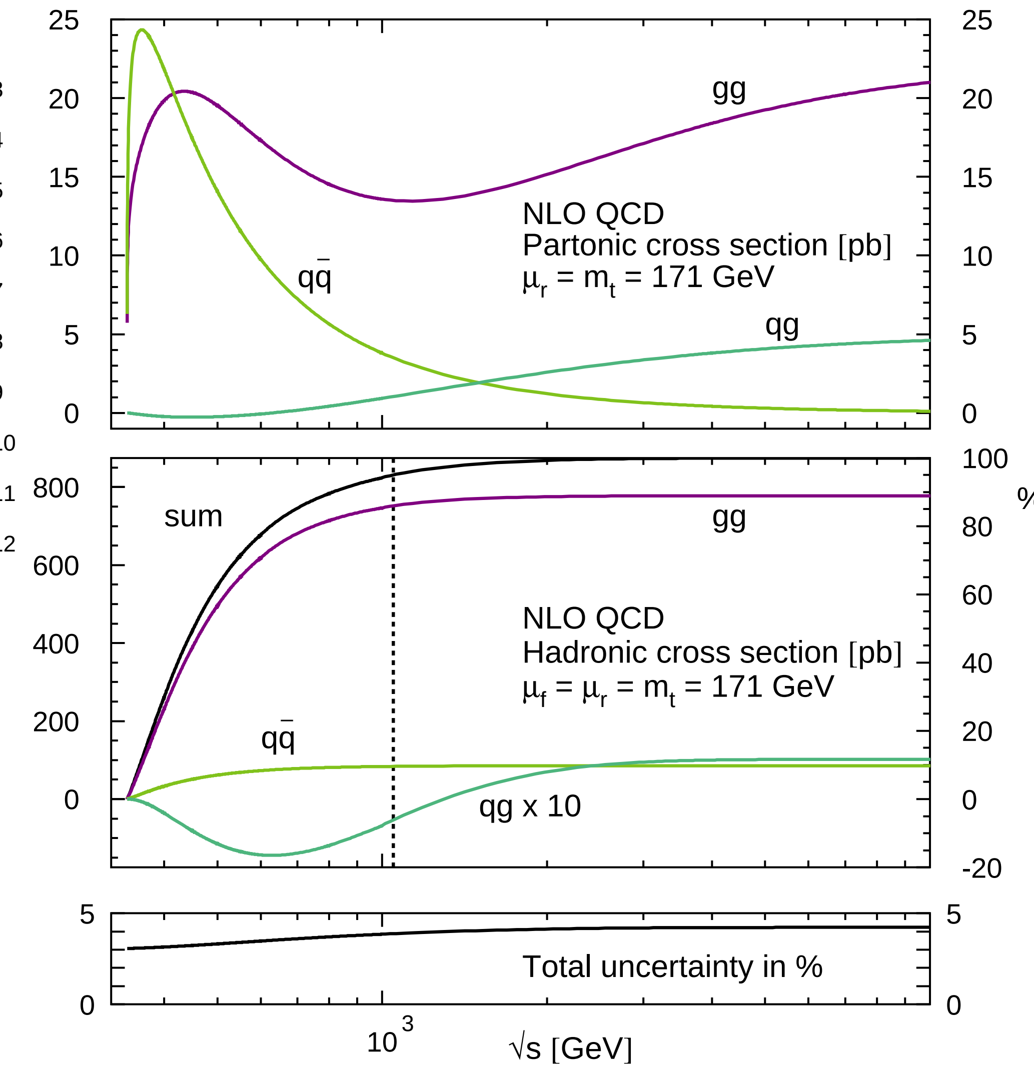
- Add all scale dependent terms
    - $\ln(\mu/m)$-terms exactly known from renormalization group methods

Upshot

- Best approximation to complete NNLO

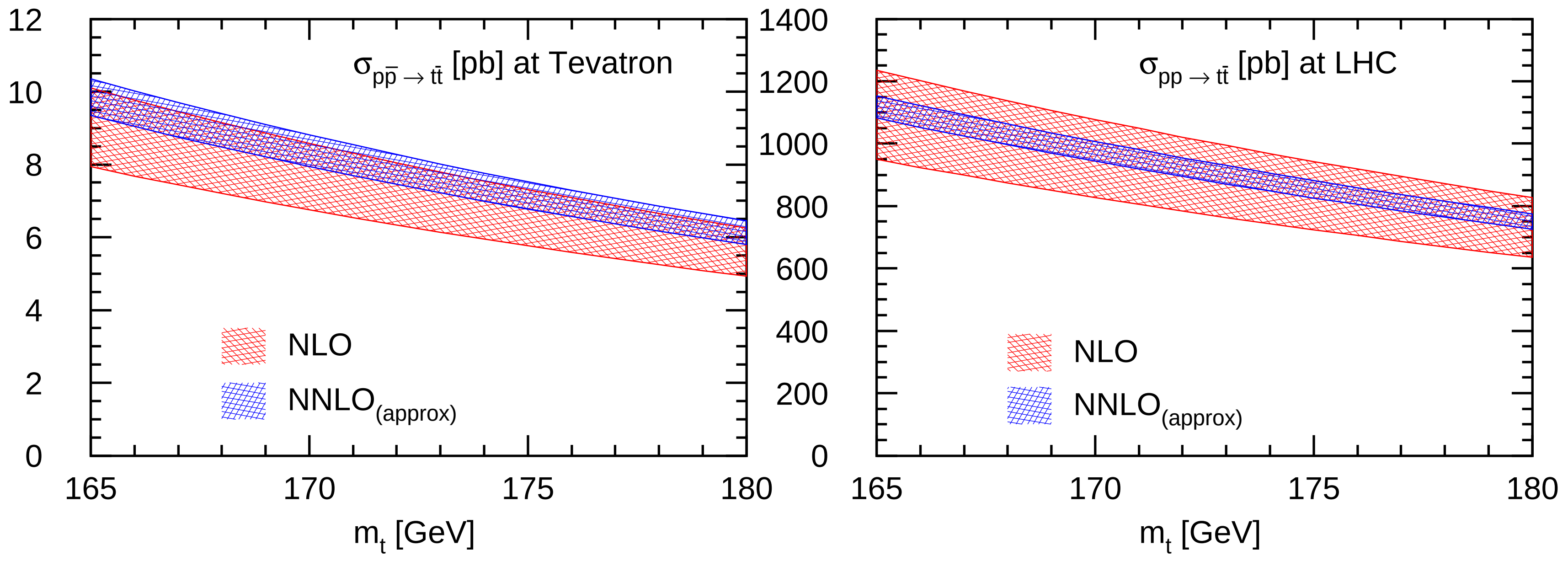
Total cross section at LHC





Top-quark pair-production at NNLO

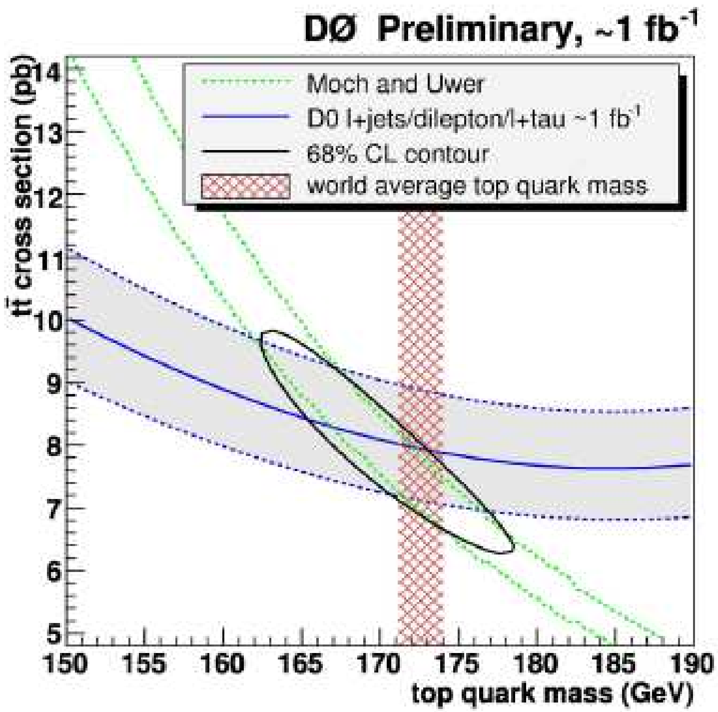
- NLO (with MRST2006 PDF set)
  - scale uncertainty $\mathcal{O}(10\%) \oplus$ PDF uncertainty $\mathcal{O}(5\%)$
- NNLO$_{\rm approx}$ (with MRST2006 PDF set)
  - scale uncertainty $\mathcal{O}(3\%) \oplus$ PDF uncertainty $\mathcal{O}(2\%)$

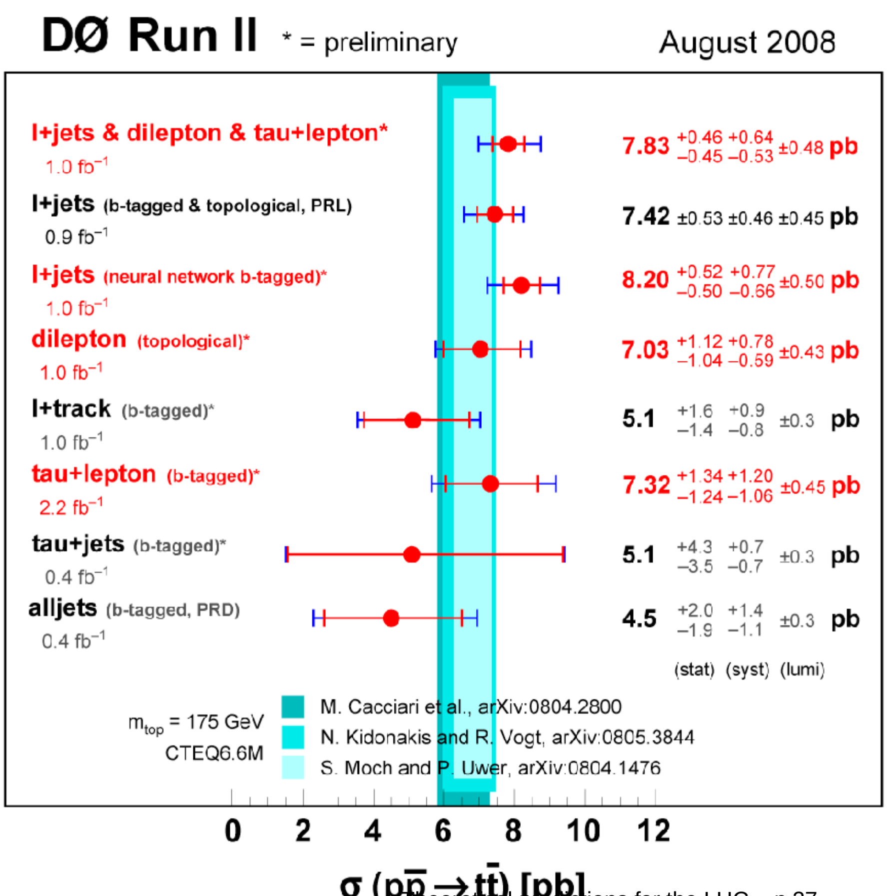


- Theory at NNLO matches anticipated experimental precision $\mathcal{O}(10\%)$

Tevatron analyses

- Total cross section and different channels of Tevatron analyses (theory uncertainty band from scale variation)
- NNLO allows for precision determinations of m_t from total cross section (slope $d\sigma/dm_t$)





Summary

Theory status at the start of LHC

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

$\longrightarrow$ talk by Anastasiou

Outlook

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

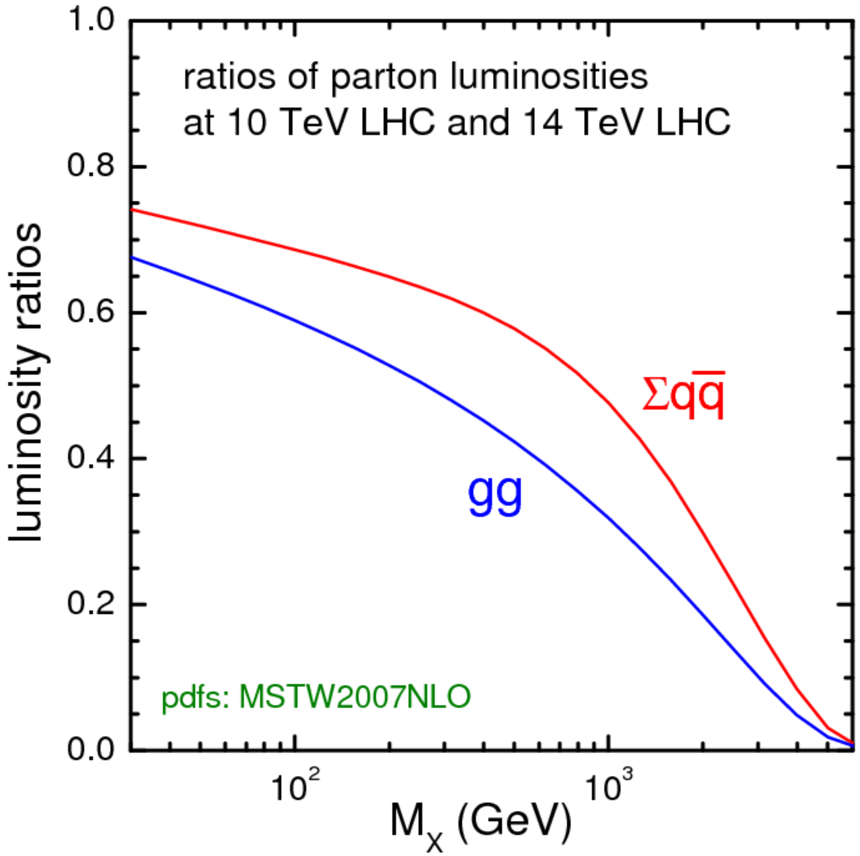
Literature

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

Back-up Slides

Initial LHC run at 10 TeV

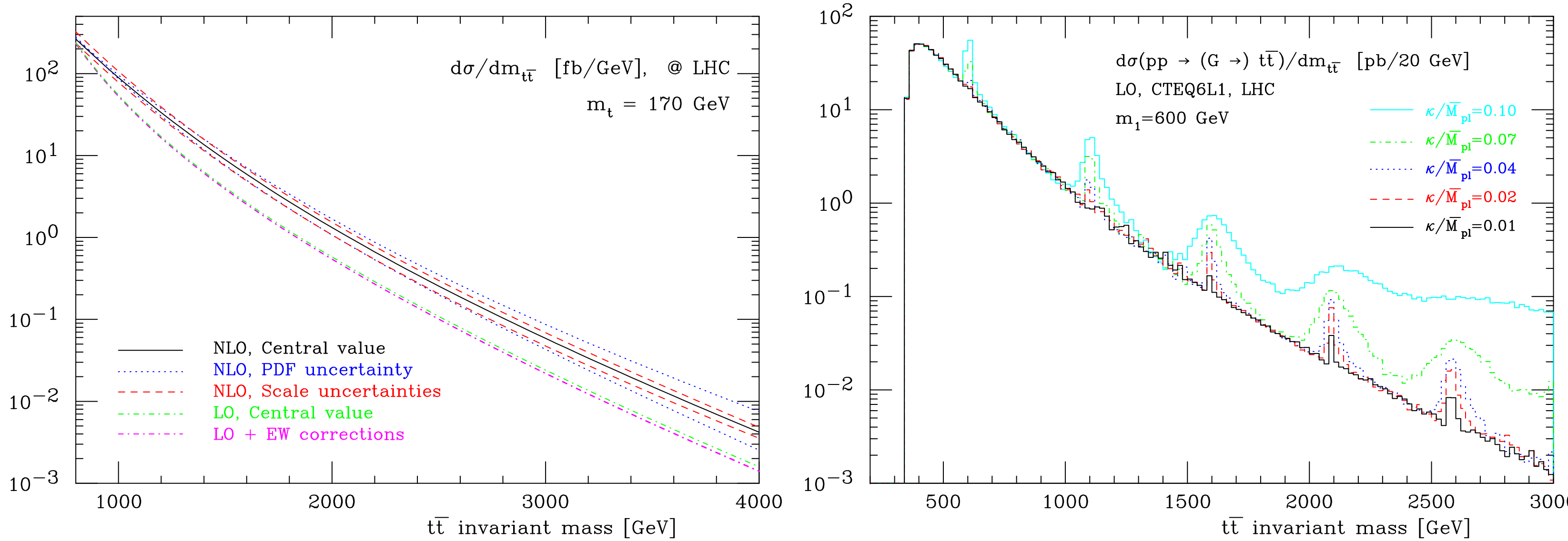
- Cross section estimates through ratio of parton luminosities
  Stirling at DIS 2008
  - less phase space for production of high mass objects at 10 TeV



- 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

Invariant mass distribution

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



- 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