Standard Model Predictions at the LHC

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DESY, Zeuthen

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- Successful experimental search relies heavily on the ability to make precision predictions for hard scattering cross-sections, e.g.
  - **Higgs** production
  - new physics phenomena (**BSM**)
  - backgrounds
  - evolution of parton distributions in proton

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  - **Higgs** production
  - new physics phenomena (**BSM**)
  - backgrounds
  - evolution of parton distributions in proton
- LHC will be a QCD machine (LEP was an electroweak machine)
  - provide accurate predictions (including QCD radiative corrections)
  - perturbative QCD is essential and established part of toolkit (we no longer “test” QCD)

W and Z boson production

- High statistics measurements of high-p_t di-leptons
  - $Z \to e^+e^-$ for calibration (ECAL uniformity, electron energy scale)
  - $Z \to \mu^+\mu^-$ for tracker alignment

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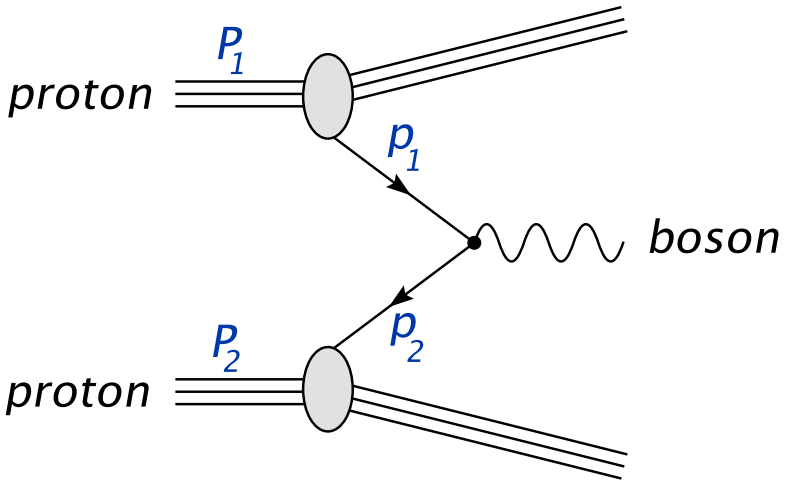
  - factorization of cross section at scale μ

$$\sigma_{\mathrm{pp}}(Q) = \sum_{\mathrm{ij}} \hat{\sigma}_{\mathrm{ij}}(Q/\mu, \alpha_s(\mu)) \otimes PDF_{\mathrm{i}}(\mu) \otimes PDF_{\mathrm{j}}(\mu)$$



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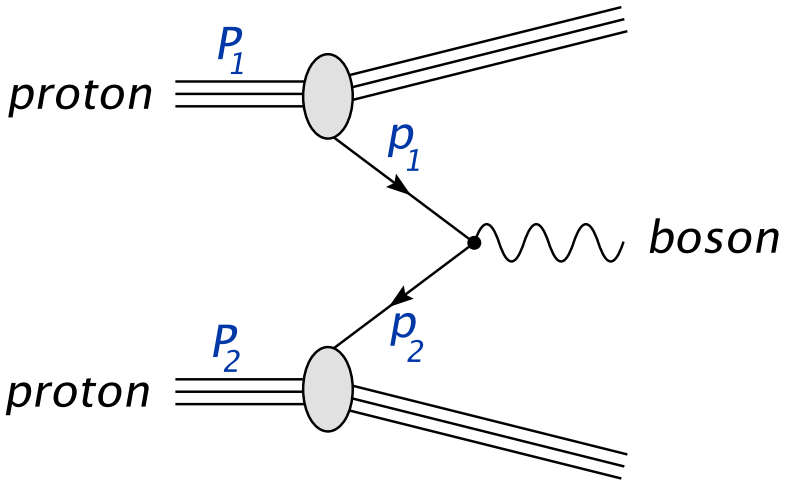
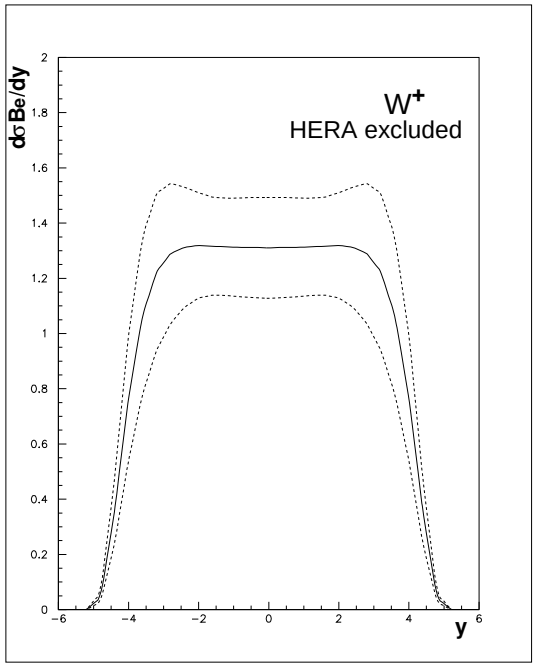
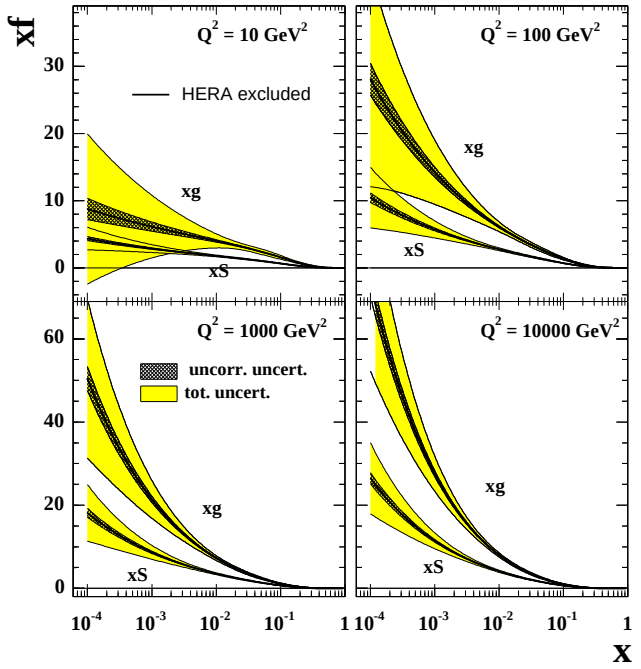


- "Standard candle" for parton luminosity $PDF_{\mathrm{i}} \otimes PDF_{\mathrm{j}}$
- Control theory uncertainties in $\hat{\sigma}_{\mathrm{ij}}$ (variation of scale μ)
  - higher order QCD predictions (NNLO) needed

W-production at the LHC

- Impact of HERA measurement on precision predictions at LHC
- LHC W^+, W^-, Z-rapidity distributions and their PDF uncertainties (NLO QCD analysis) Tricoli, Cooper-Sarkar, Gwenlan '05
  - cross section uncertainty 16% **without** HERA PDFs (left)
  - proton PDFs **without** HERA data (right)





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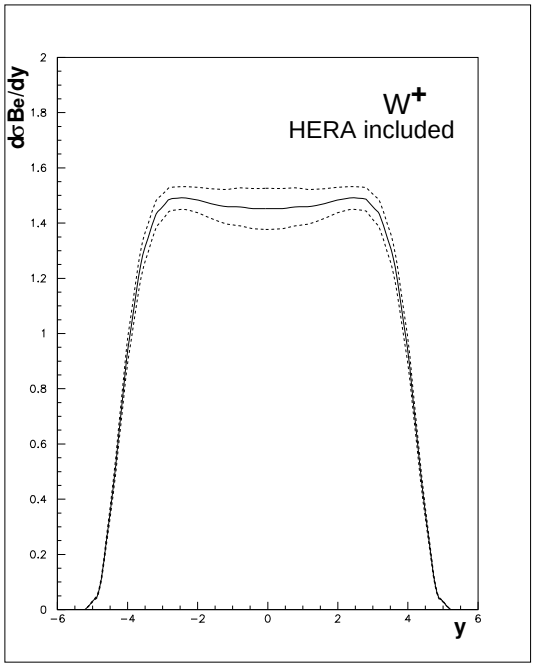
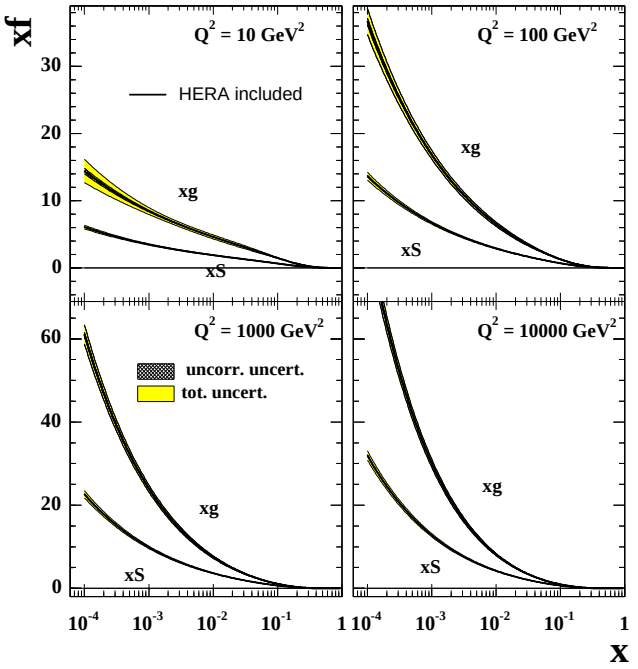
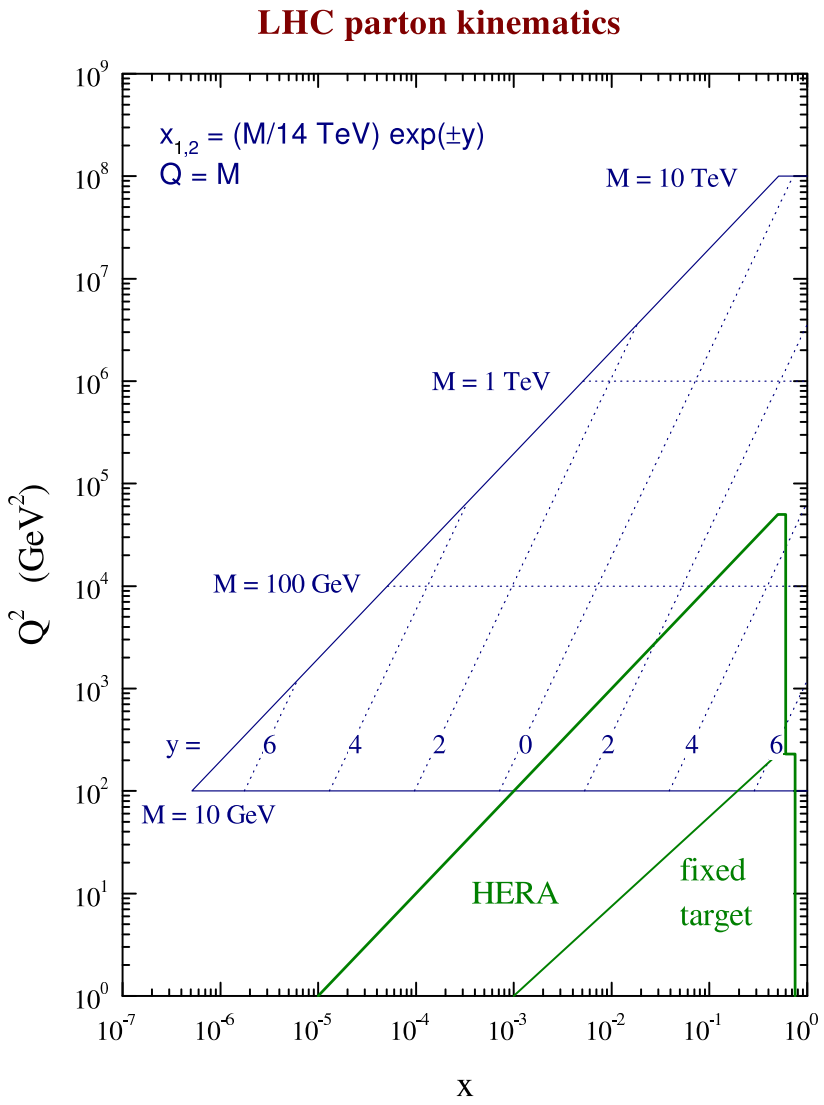
  - cross section uncertainty 3.5% **with** HERA PDFs (left)
  - proton PDFs **with** HERA data (right)





PDFs from HERA to LHC



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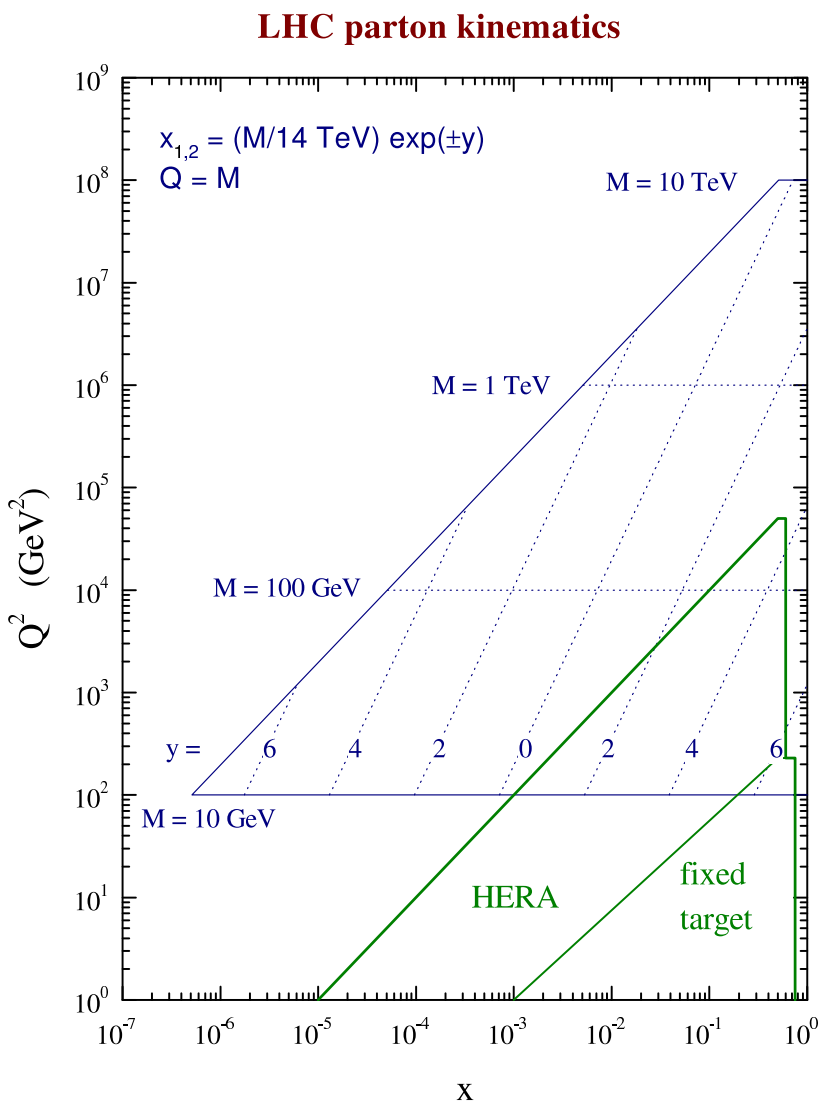

- Precision in QCD evolution of PDF

$$\frac{d}{d\ln Q^2} PDF(x,Q^2) = \left[P(\alpha_s(Q^2)) \otimes PDF(Q^2)\right](x)$$

- Control of theory uncertainty requires NNLO QCD predictions
  - three-loop splitting functions
    S.M., Vermaseren, Vogt '04

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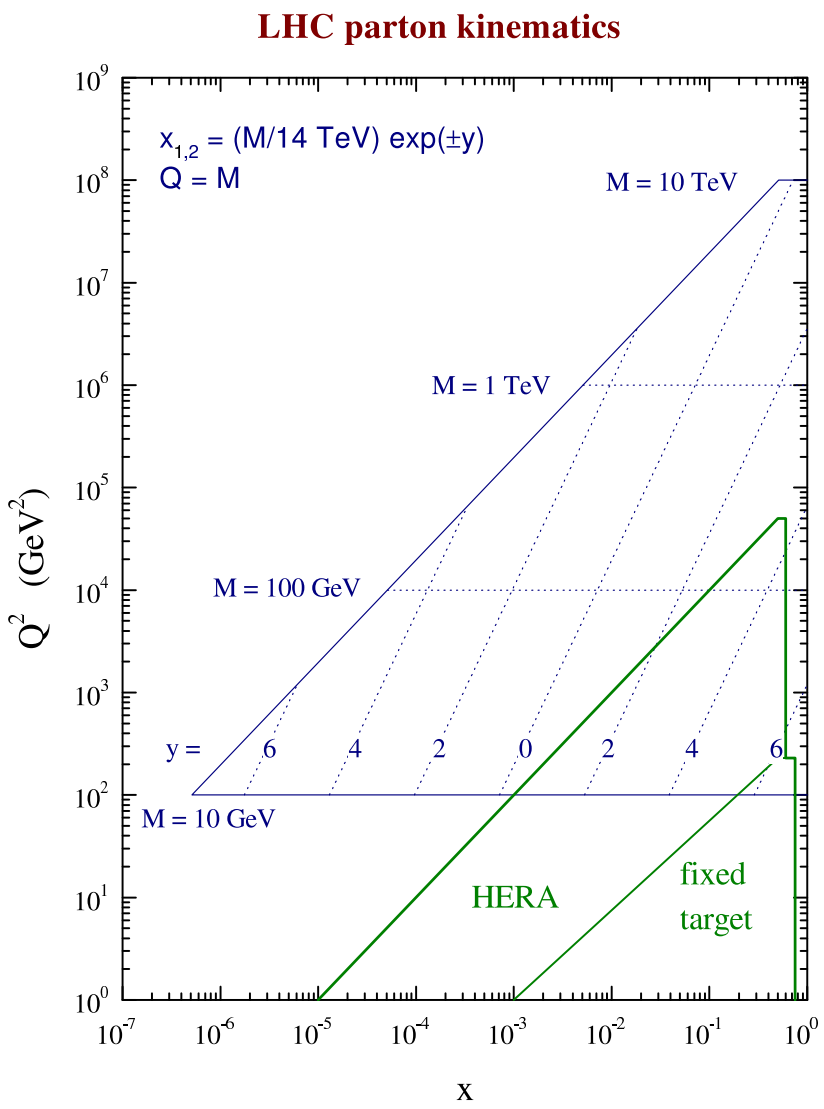

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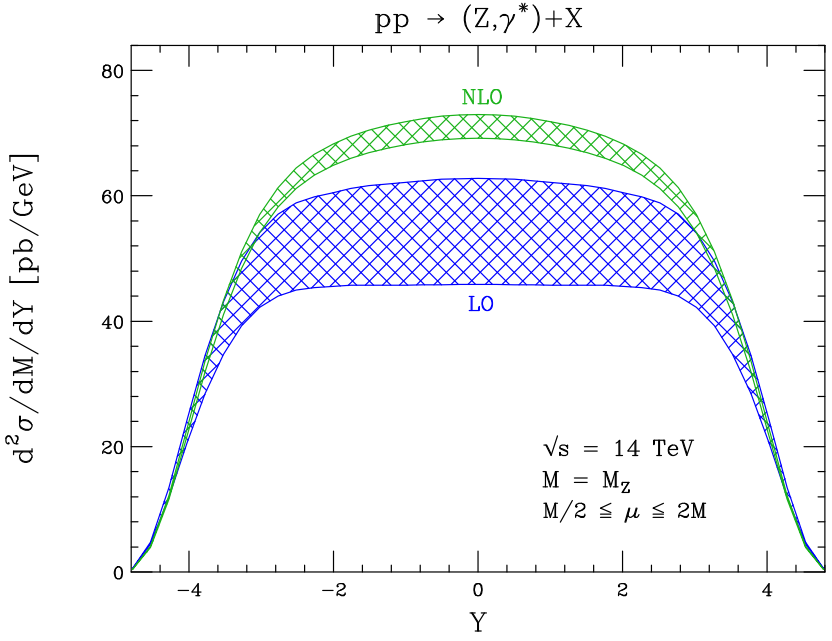
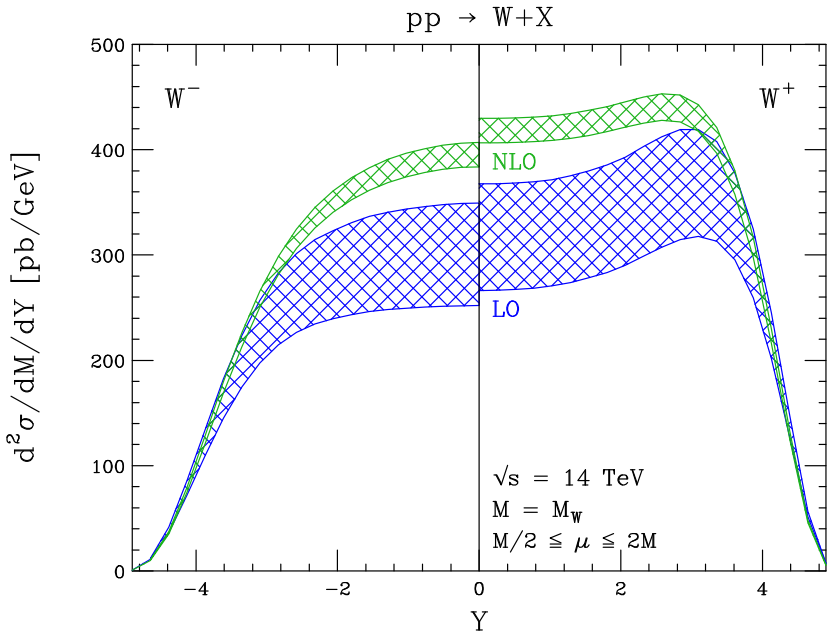
- tools: QCD-PEGASUS Vogt
  (evolution code at NNLO in Mellin N-space)

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

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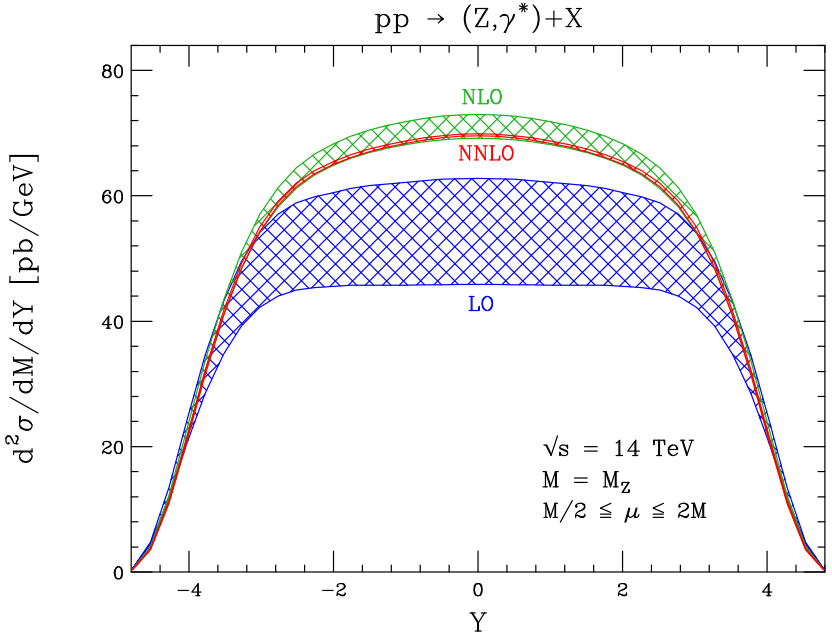

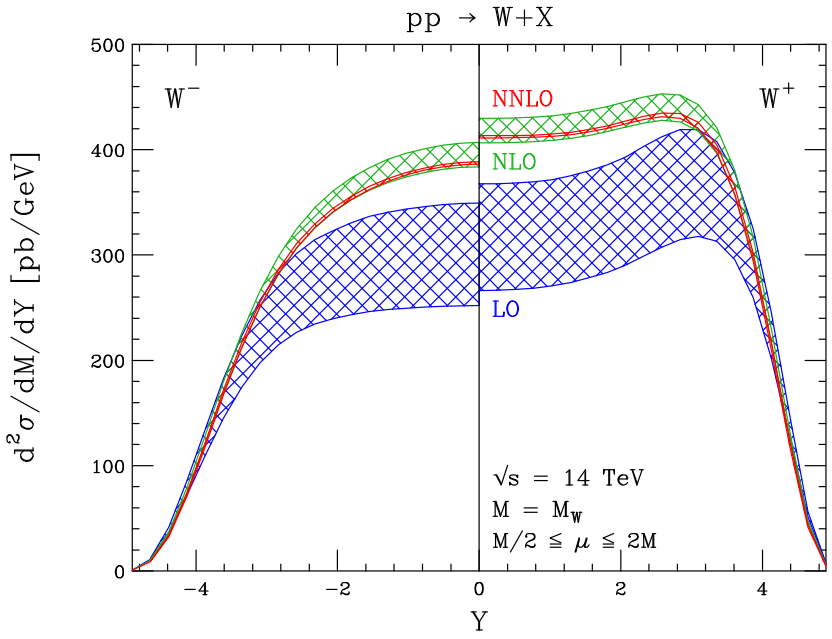

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Top-quark pair production

Experimental expectations

- LHC will accumulate very high statistics for $t\bar{t}$-pairs
  - $8 \cdot 10^6$ events/year in low luminosity run
    (10 time more in high luminosity run)
  - mass measurement $\Delta m_t = \mathcal{O}(1)$GeV
    (constraints on Standard Model Higgs mass m_h)
- Use $t\bar{t}$-pairs for calibration of jet energy scale (decay $W \to 2\,$jets)

Theory predictions

- Higher order QCD corrections essential
  - NLO in QCD accurate to $\mathcal{O}(10\% - 15\%)$ at LHC
  - Threshold resummation important (however, less than at Tevatron)
- NNLO required for precision determinations of m_t
- tools: HVQMNR Mangano, Nason, Ridolfi
  (NLO double-differential distributions for $t\bar{t}$)

Gentile (DESY seminar June 07, 2006)

Top Mass from Semi-Leptonic Events

SOURCE	Gauss[Gev]	Ideo [GeV]
Pile-Up	0.32	0.21
Underlying event	0.50	0.25
Light jet energy scale	1.80	0.06
Heavy jet energy scale	1.05	0.90
Radiation (QCD)	0.80	0.22
Fragmentation	0.40	0.30
b-tagging	0.80	0.18
background	0.30	0.25
Parton Density Functions	0.12	0.08
Total systematic uncertainty	3.21	1.13
Statistical Uncer($10fb^{-1}$)	0.32	0.21
TOTAL: Stat ⊕ Syst	3.23	1.15

➢ **$\Delta M_{top} < 2$ GeV feasible**

▪ **$\Delta M_{top} < 1$ GeV challenge**

Most important Experimental:

- b-jet energy scale
- Pile-up

•Improvement applying event-by-Event convolution method

Zeuthen, 7th June, 2006

Renormalization / Factorization scale dependence

- If $Obs = \sum_{n=0}^{N} A_n(\mu)\alpha_s^n(\mu)$, then $\frac{\partial}{\partial \ln \mu} Obs = \mathcal{O}(\alpha_s^{N+1})$
- Scale variation produces only copies of lower order terms, i.e. dependence on $\ln \mu$ is entirely predictable

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- Total cross section for $t\bar{t}$-production with $L = \ln(\mu^2/m_t^2)$

$$\sigma_{t\bar{t}} = \alpha_s^2(\mu)A_0 + \alpha_s^3(\mu)\{A_1 + Lf_1(A_0, \beta_0, P_0)\}$$

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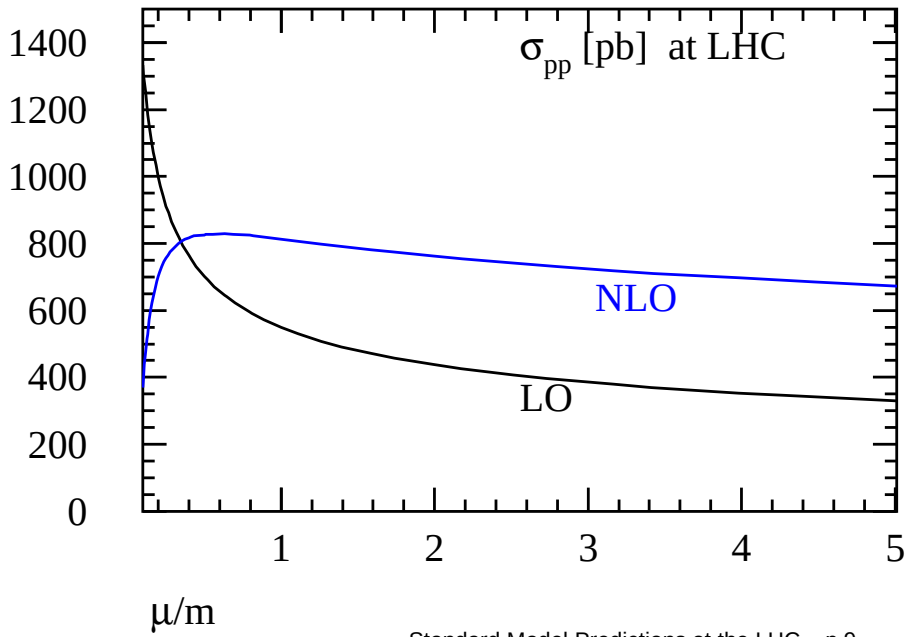
- $\sigma_{t\bar{t}}$ ($q\bar{q}$ and gg-channel) at LO, NLO



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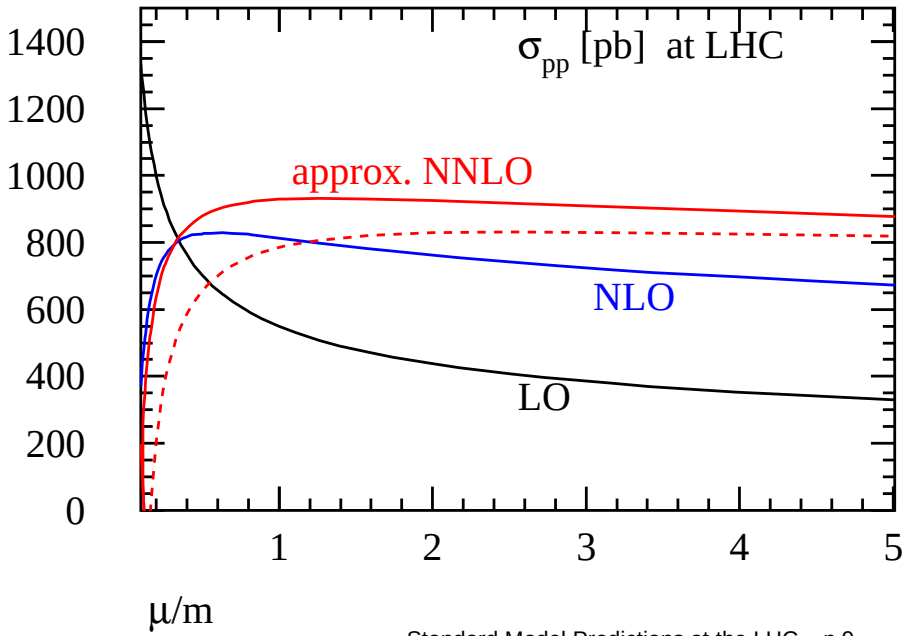
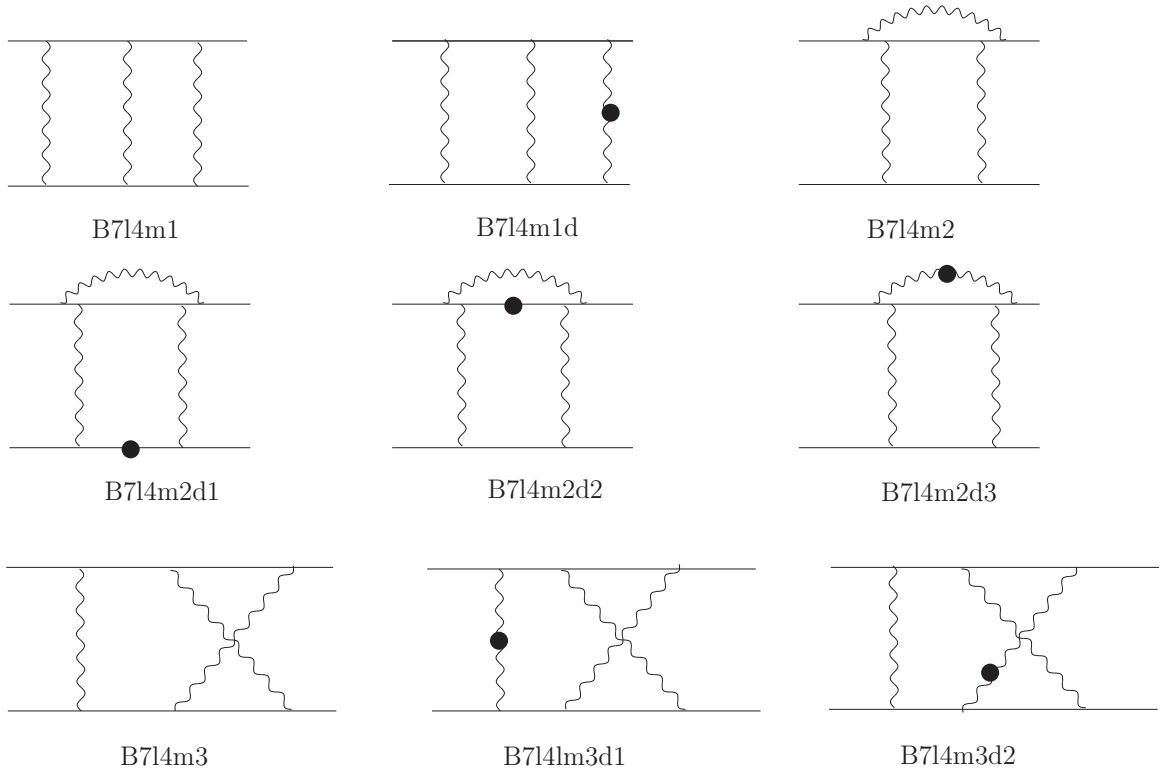
$$\begin{aligned}\sigma_{t\bar{t}} &= \alpha_s^2(\mu)A_0 + \alpha_s^3(\mu)\{A_1 + Lf_1(A_0,\beta_0,P_0)\} \\ &\quad + \alpha_s^4(\mu)\left\{A_2 + Lf_2(A_0,A_1,\beta_0,\beta_1,P_0,P_1) + L^2 f_3(A_0,\beta_0,P_0)\right\}\end{aligned}$$

- $\sigma_{t\bar{t}}$ ($q\bar{q}$ and gg-channel) at LO, NLO and with NNLO exact scale dependence assuming
  - $A_2 = (A_1)^2/2$ (solid) consistent with threshold exponentiation
  - $A_2 = 0$ (dotted)

  for $\sqrt{s} = 14\text{TeV}$, $m_t = 175\text{GeV}$



Two-loop QED corrections to Bhabha scattering



- Complete set of master integrals for massive two-loop Bhabha
  Czakon, Gluza, Riemann '04

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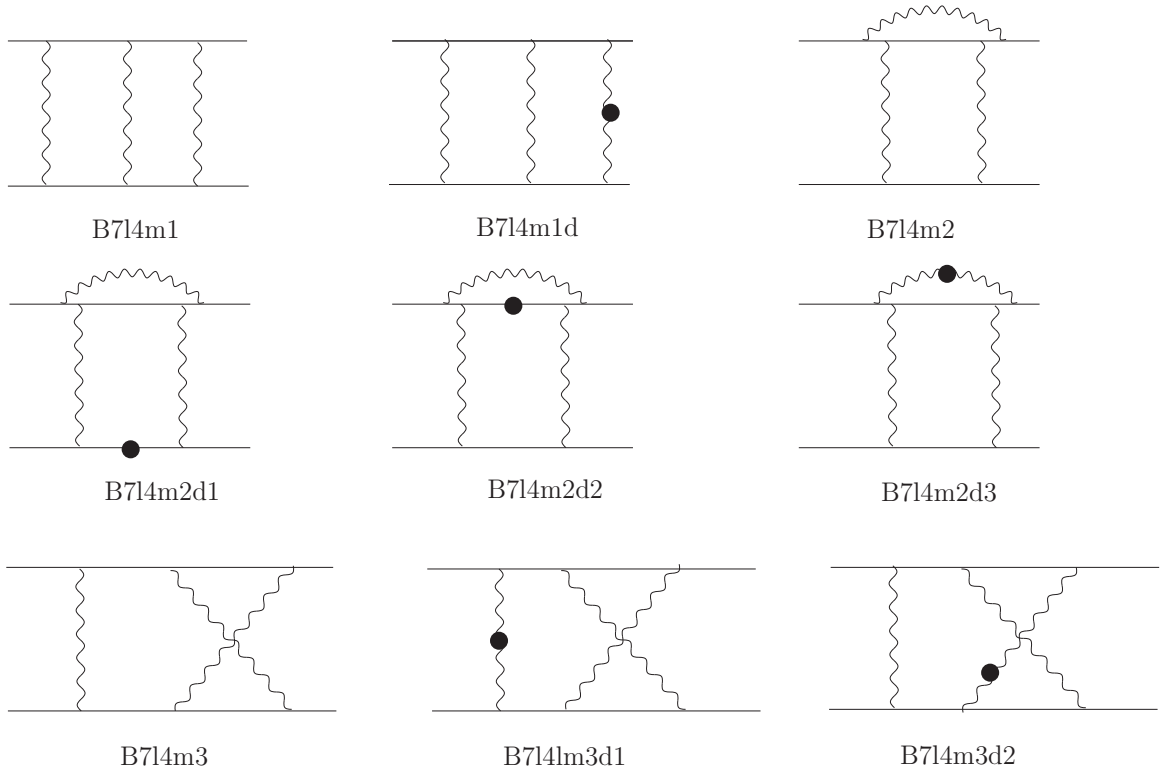
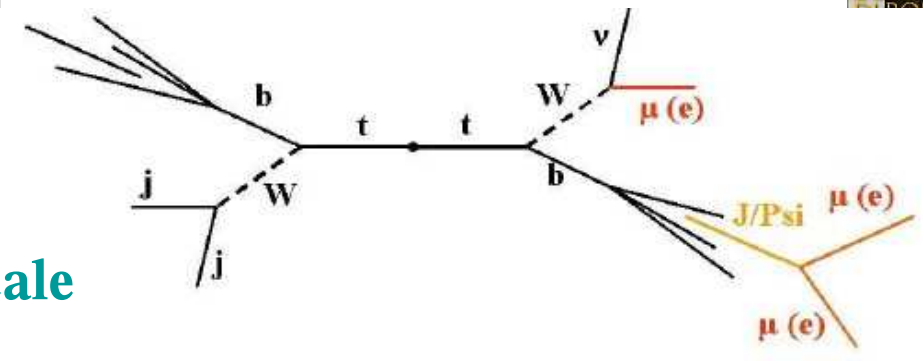


- Complete set of master integrals for massive two-loop Bhabha
  Czakon, Gluza, Riemann '04
- **Test ground** for multi-loop calculations with multiple scales
  - development of key technology (Laporta algorithm, differential equations, Mellin-Barnes representations, nested sums, ...)

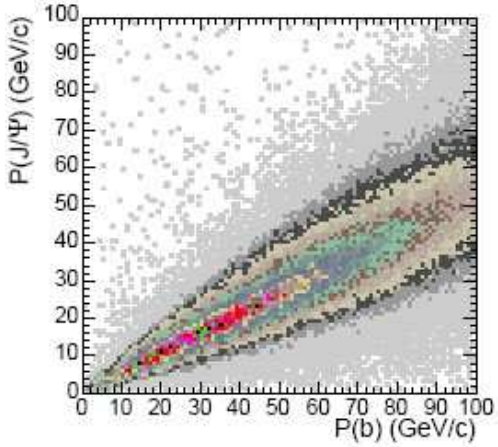
Gentile (DESY seminar June 07, 2006)

Top Mass from J/Ψ

- **Method:**
  Partial reconstruction of top J/Ψ + lepton



- **indipendent of jet energy scale**
- **$M_{inv}^{3\ell}$ correlated m_t**



- **Low BR($tt \to Wb+qqJ/\psi \to \ell\ell$) ≈ 5.5 10^{-5}**
- **efficiency (ε ~ 20%)**
- **Low background**
- **limited by b fragmentation & needs high luminosity**

1000 events/y @ 10^{34}

New

CMS-Note2006/058 8 May 2006

Progress towards b fragmentation at NNLO

Mitov, S.M. *work in progress*

- Fragmentation $b \to B$ is non-perturbative, but process independent
- Single-particle disributions sensitive to $b \to B$ transition
  - p_T-distribution (hadron colliders)
  - energy spectra (e^+e^--collider)
  - top mass precision measurement, e.g. from J/ψ in t-decay
- Perturbative heavy-quark fragementation Mele, Nason '91

$$\frac{d\sigma_B}{dp_T} = \frac{d\sigma_b}{dp_T} \otimes D^{\rm DGLAP} \otimes D^{ini} \otimes D^{\rm np}_{b\to B} \qquad \text{measured at LHC}$$

$$\frac{d\sigma_B}{dp_T} = \frac{d\sigma_b}{dp_T} \otimes D^{\rm DGLAP} \otimes D^{ini} \otimes D^{\rm np}_{b\to B} \qquad \text{measured in } e^+e^-$$

- Ingredients at NNLO
  - coefficient functions at two-loops Rijken, van Neerven '96; Mitov, S.M '06
  - heavy quark initial conditions D^{ini} Mitov, Melnikov '04
  - time-like (non-)singlet splitting functions Mitov, S.M, Vogt '06
- Universal non-perturbative function $D^{\rm np}_{b\to B}$ ("left-over" data – pQCD)

QCD jets

Lessons from Tevatron

- Top search was the outstanding issue at the start of run I at Tevatron
- Initiated many developments in LO multi-parton generation for $pp \to W^{\pm} + \text{jets}$ (e.g. numerical recursion, algebraic generation of tree level amplitudes)
  - unexpected challenge: importance of matching issues between matrix elements and shower Monte Carlo's
  - initiated development of "numerical" partonic NLO jet Monte Carlo's

Expectations for LHC

- In the coming years
  - all new challenges for NLO are encapsulated by Higgs searches at ATLAS/CMS
  - large number of high multiplicity processes

Experimenter's wishlist

process ($V \in \{\gamma, W^{\pm}, Z\}$)	background to
$pp \to VV + 1$ jet	$t\bar{t}H$, new physics
$pp \to H + 2$ jets	H production by vector boson fusion (VBF)
$pp \to t\bar{t}b\bar{b}$	$t\bar{t}H$
$pp \to t\bar{t} + 2$ 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

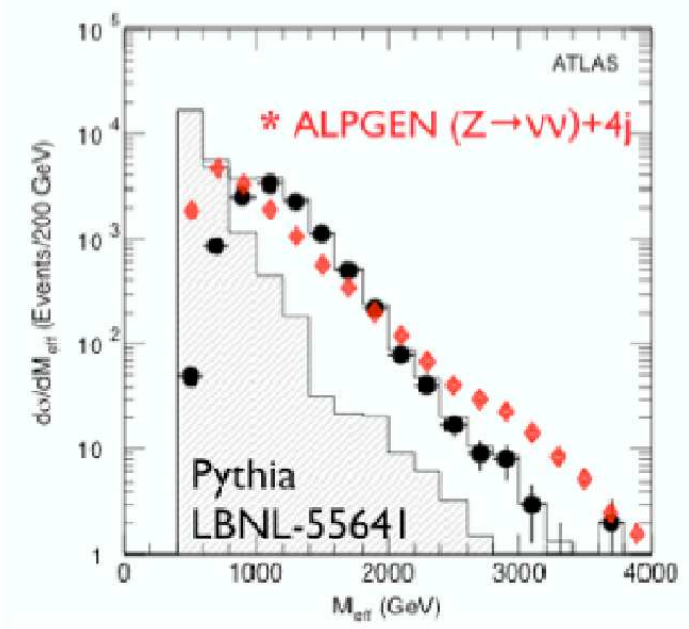
Bern (extracted from *Tevatron Run II Monte Carlo workshop April 2001*)

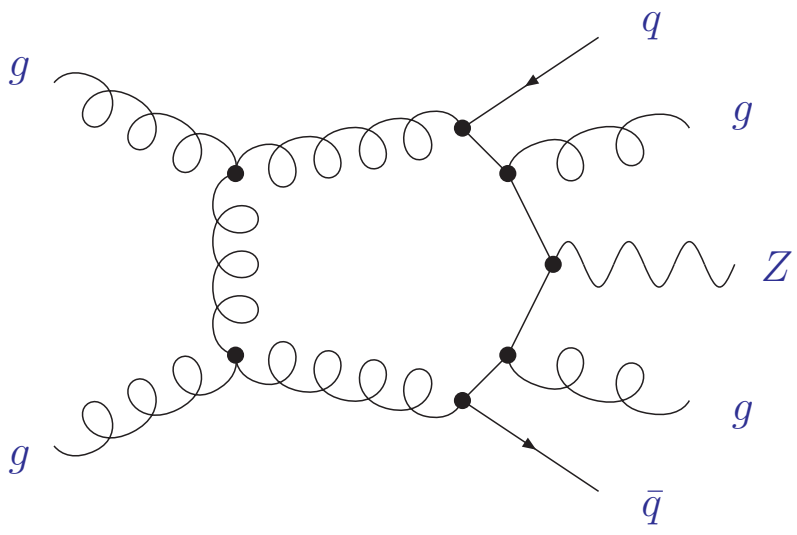
The original experimenter's wishlist

Run II Monte Carlo Workshop, April 2001

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

SUSY searches





- Early ATLAS TDR studies with Pythia are overly optimistic
- Alpgen
  - based on leading order matrix elements
  - models hard jets much better
- Significance of potential disagreement between data and Alpgen ?
- Need for $pp \to Z + 4\,\text{jets}$ at NLO

Perturbative QCD corrections essential

- NLO important for rates (background); large K-factors, new parton channels may dominate beyond tree level
  - e.g. $W + 4$ jets is $\mathcal{O}(\alpha_s^4)$ and $\Delta(\alpha_s^{\rm LO}) \simeq 10\%$ gives $\Delta(\sigma^{\rm LO}) \simeq 40\%$

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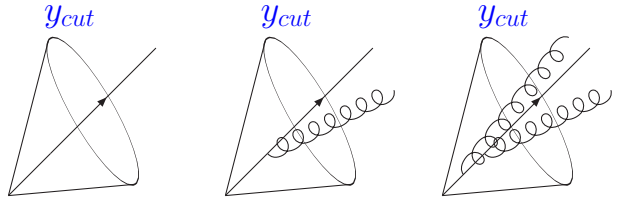
- NNLO (for di-jets) important for scale uncertainty, PDF determination, modelling of jets, ...



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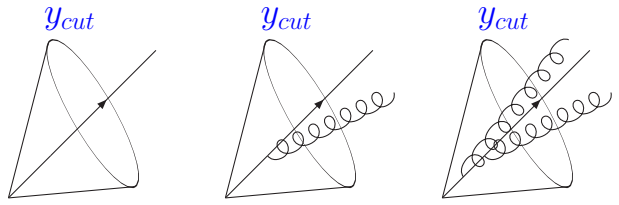

- Hadronic di-jets: large statistics even with high-p_t cuts
  - gluon jets constrain gluon PDF at medium/large x
  - searches for quark sub-structure (di-jet angular correlations)
  - experimental calibration (HCAL uniformity, establish missing E_t)

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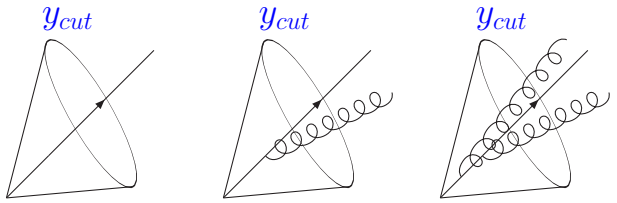

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Progress in theory

- Recent developments in amplitudes for multi-particle production
  - twistor space methods and recursion relations
- Numerical phase space integration: tedious, NNLO very difficult

Theory developments at NLO

- Tools from computation of tree level amplitudes $\mathcal{A}$
  - color ordering

    $$\mathcal{A}_n^{\text{tree}} = g^{n-2} \sum_{\sigma \in S_n/Z_n} \text{Tr}(T^{a_\sigma(n)} \dots T^{a_\sigma(n)}) A(\lambda_\sigma(1), \dots, \lambda_\sigma(n))$$

  - helicity amplitudes ($\lambda_i = i^{\pm}$), e.g. MHV Parke, Taylor '86

    $$A(1^-, 2^-, 3^+, \dots, n^+) = \text{i} \frac{\langle 12 \rangle^4}{\langle 12 \rangle \langle 23 \rangle \dots \langle n1 \rangle}$$

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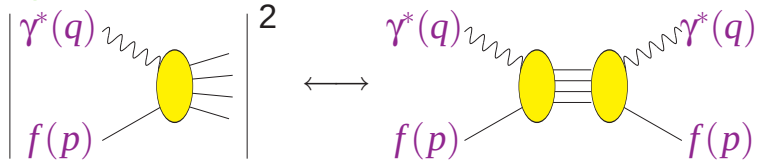
  - Unitarity (cutting rules) Cutkosky; ...



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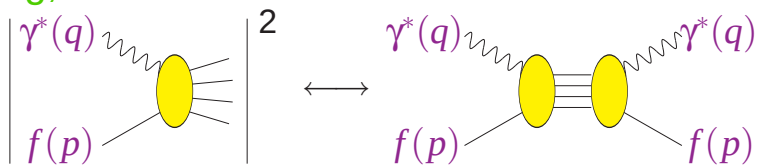


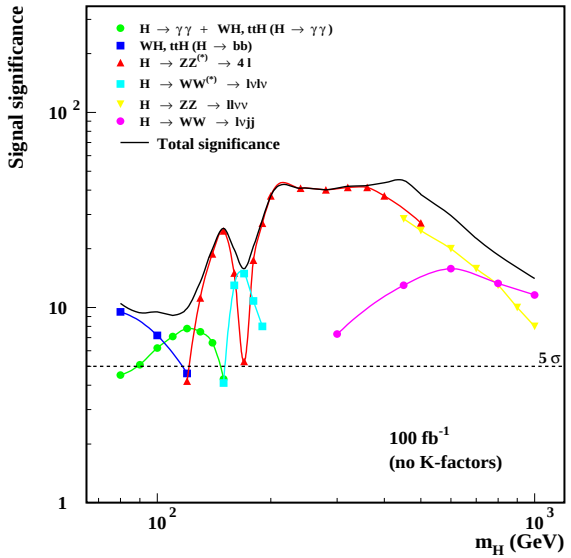
  - Factorization (soft/collinear limits)
- **Upshot:** constructive approach at NLO (very promising)
  - a lot of recent activity Bern, Kosower, Dixon, Berger, Forde; Dunbar, Bidder, Bjerrum-Bohr; Britto, Buchbinder, Cachazo, Feng, Mastrolia; Glover, Zanderighi, Ellis, Giele; *+ many others*

Tools for jets in cross section

- Selected general purpose tools for observables with jets (and heavy quarks, weak gauge bosons, ...)
  - tools: NLOjet++ Nagy
    (multipurpose C++ library for calculating jet cross sections)
  - tools: MCFM Campbell, Ellis
    (vector bosons, Higgs and jets at hadron colliders)
  - tools: MC@NLO Frixione, Nason, Webber
    (combines Monte Carlo event generator with NLO calculations)
  - tools: PHOX family
    Aurenche, Binoth, Fontannaz, Guillet, Heinrich, Pilon, Werlen
    (processes involving photons, hadrons and jets)
- Evaluation of differential cross sections in PDF fits
  - tools: fastNLO Kluge, Rabbertz, Wobisch
    (PDF fits including jet data)

Higgs production

- Importance of channels for searches depended on Higgs mass m_H



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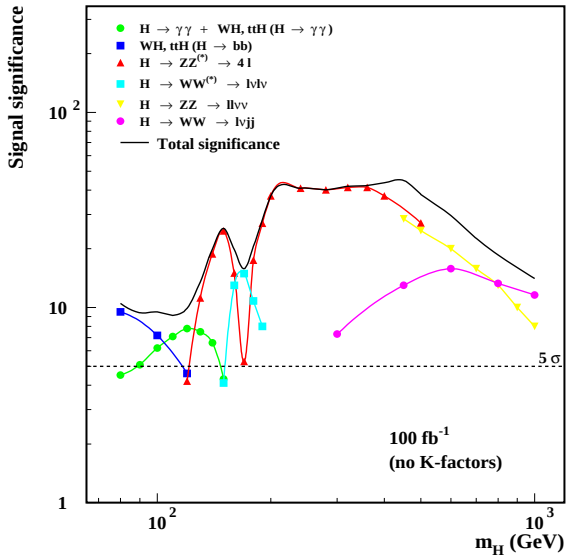

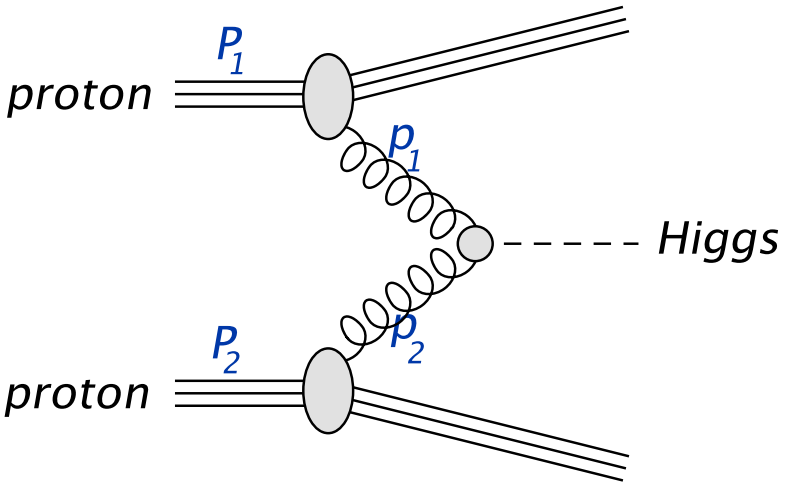

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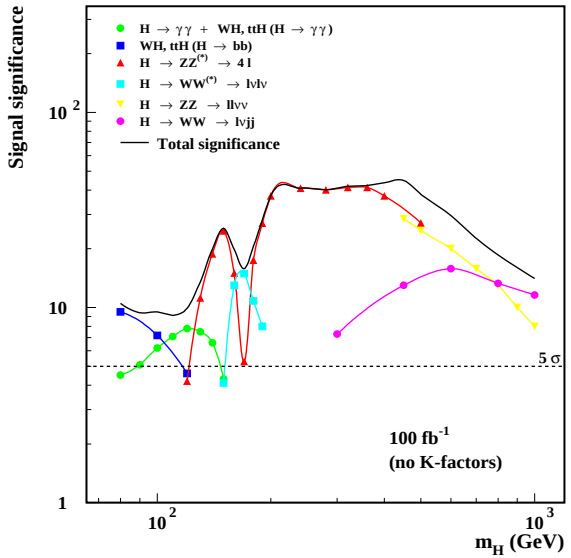
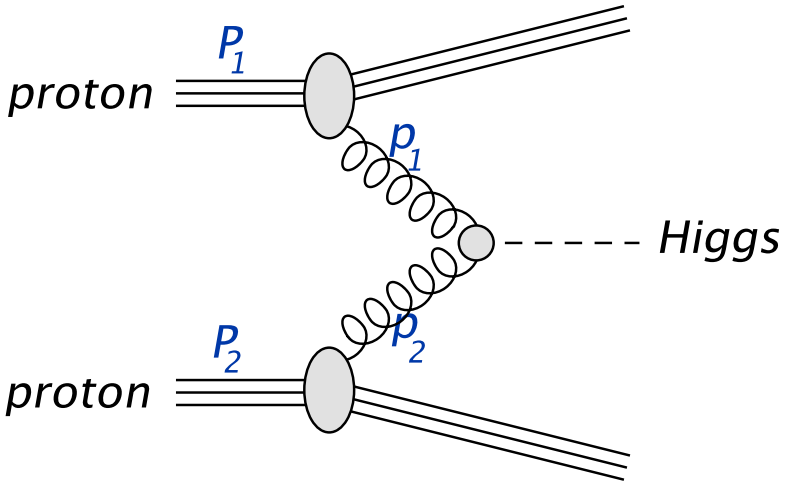
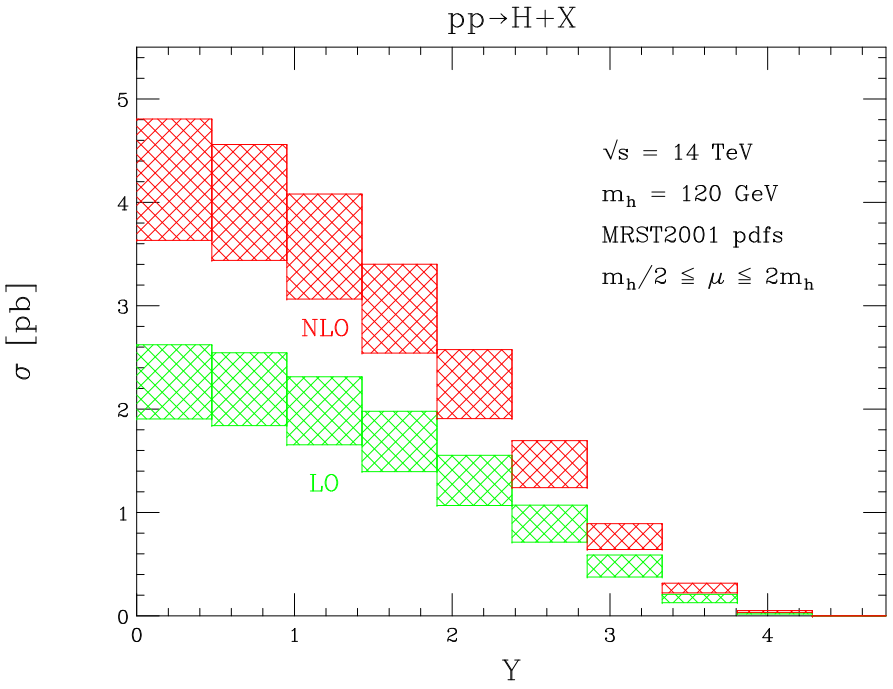
- This talk:
  - focus on precision predictions in QCD
  - control of theory uncertainties at NNLO in QCD





Rapidity distribution at NNLO in QCD



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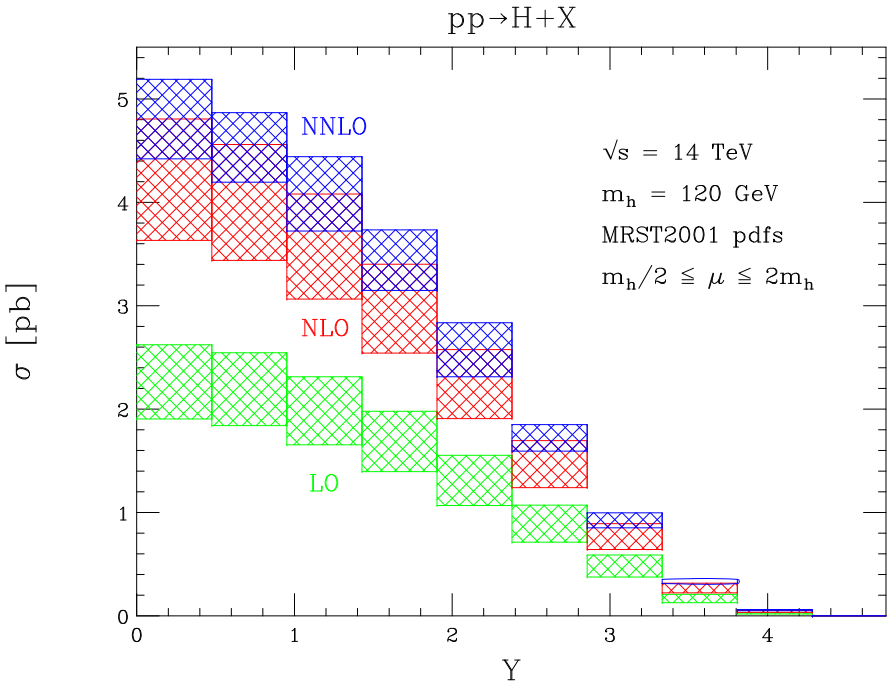

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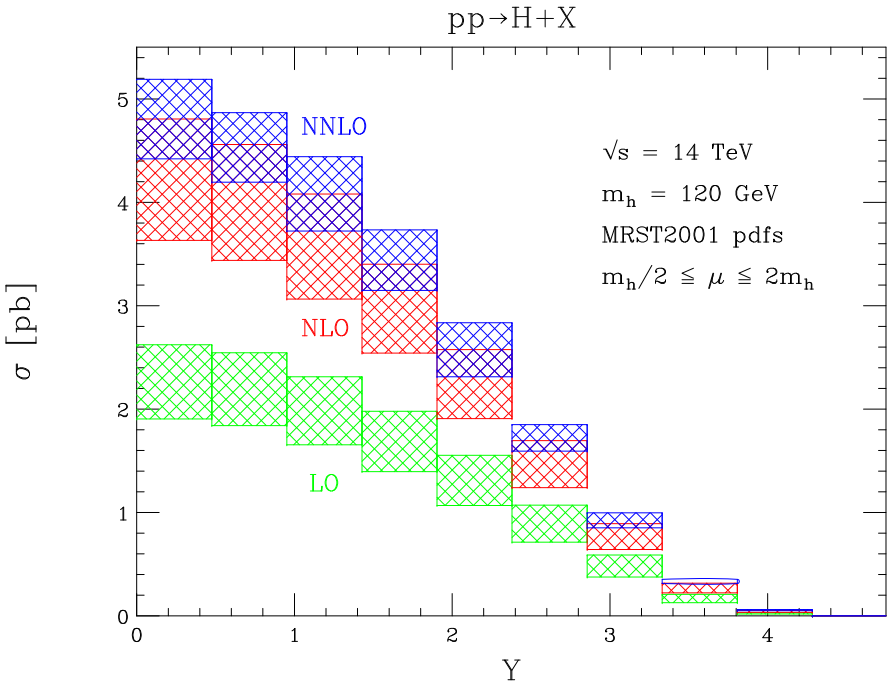

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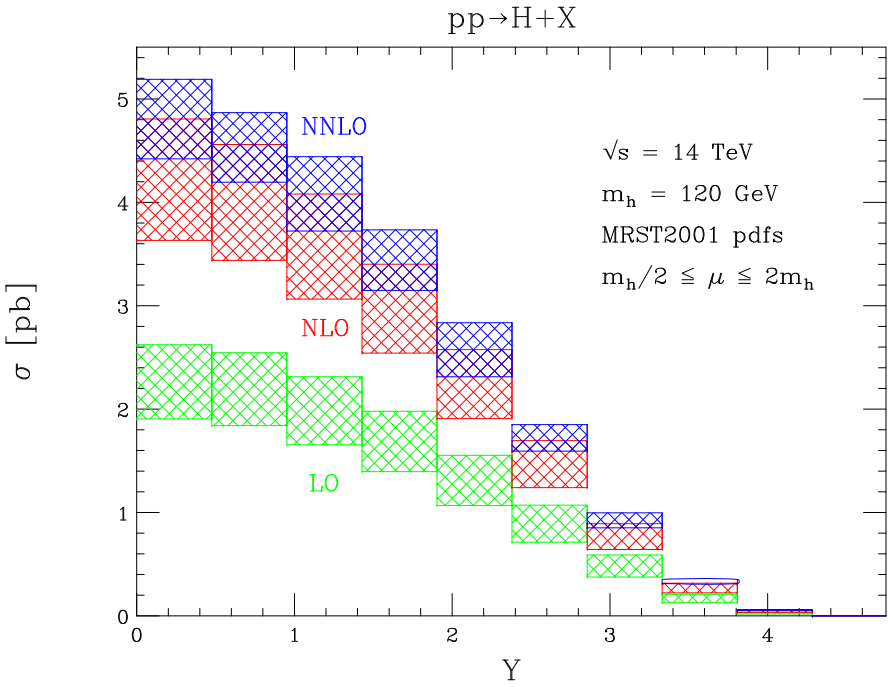

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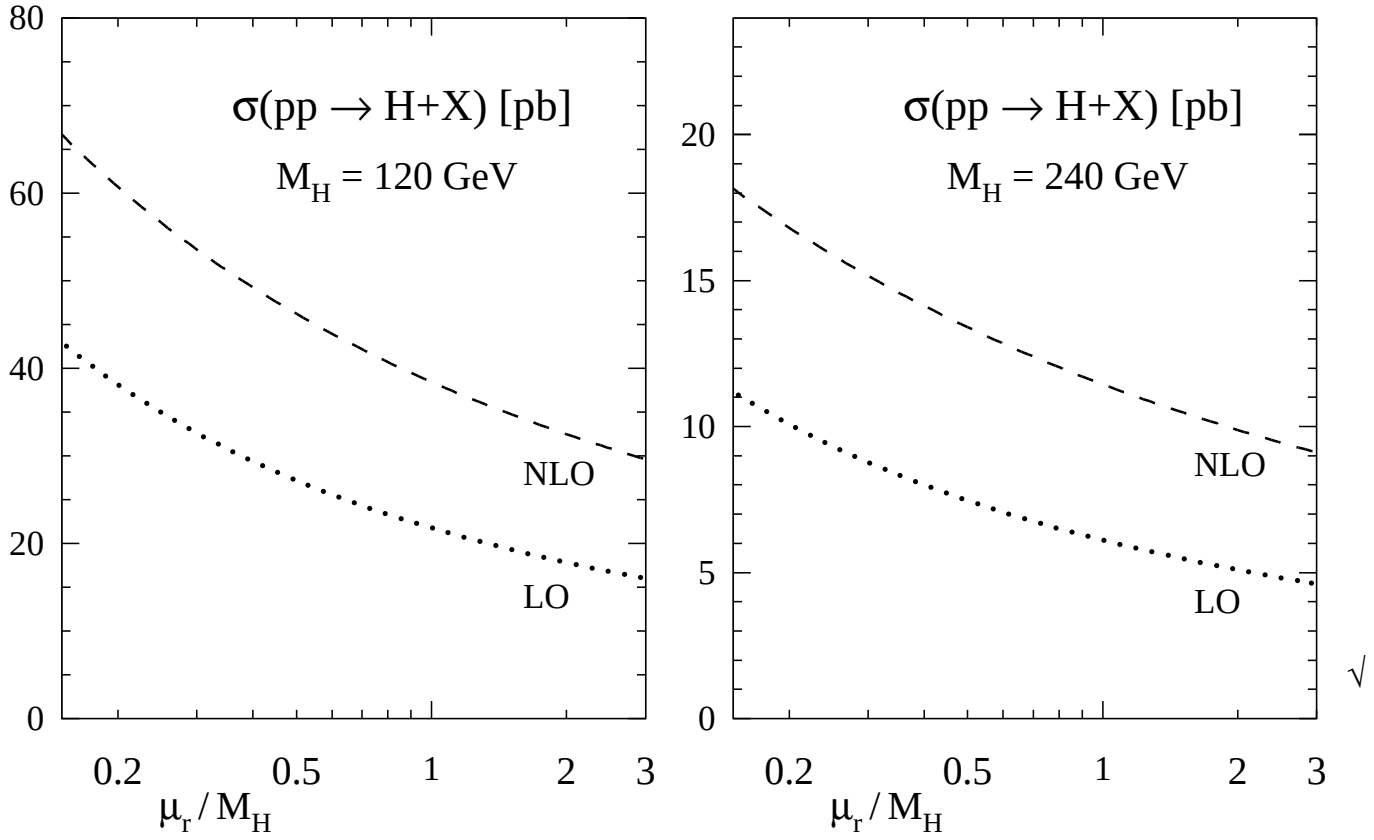
  - N^{3}LO results with $x = m_h^2/s$ S.M., Vogt '05

$$c_3^{\rm Higgs} = \left(\frac{\ln^5(1-x)}{(1-x)}\right)_+ \left\{512 C_A^3\right\} + \cdots + \frac{1}{(1-x)_+}\left\{\ldots\right\}$$

Cross section Higgs production (cont'd)



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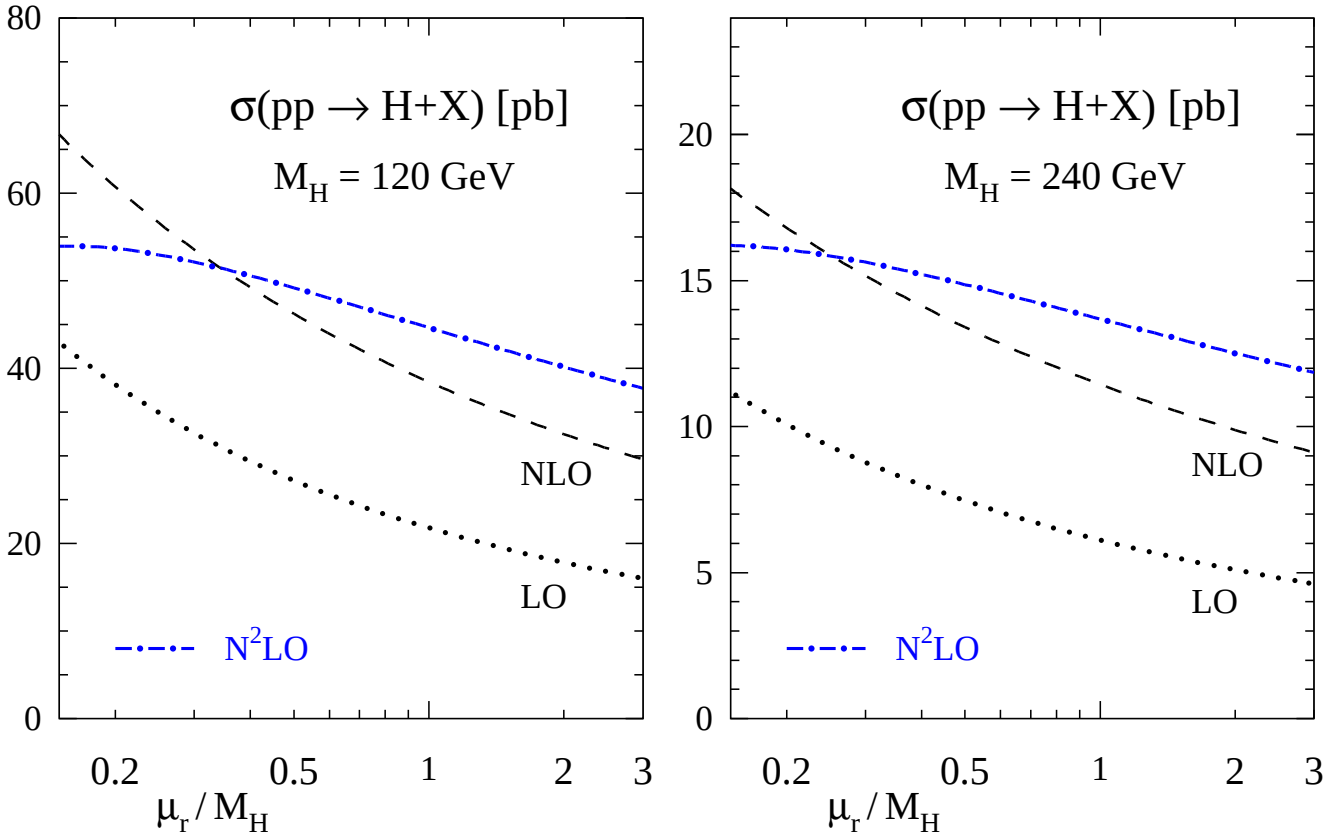

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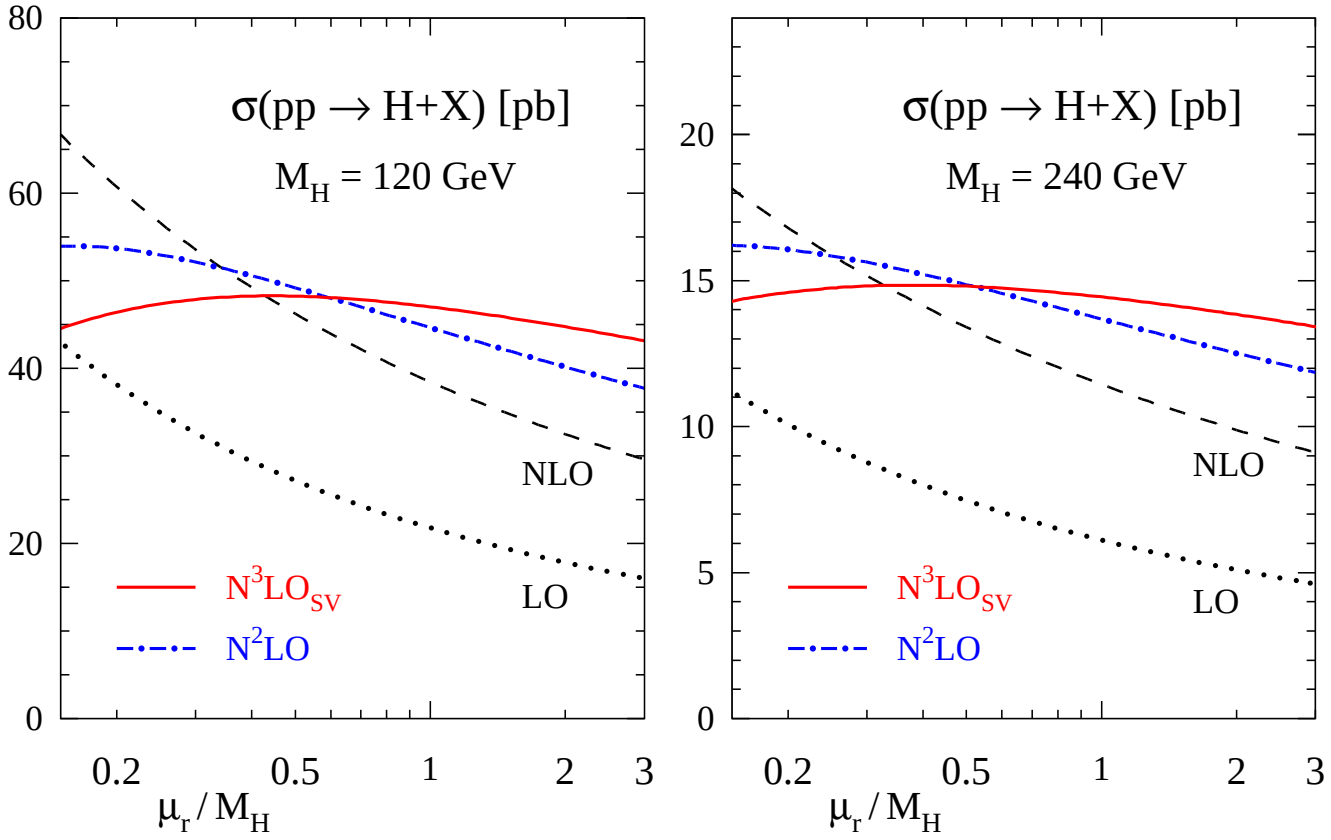

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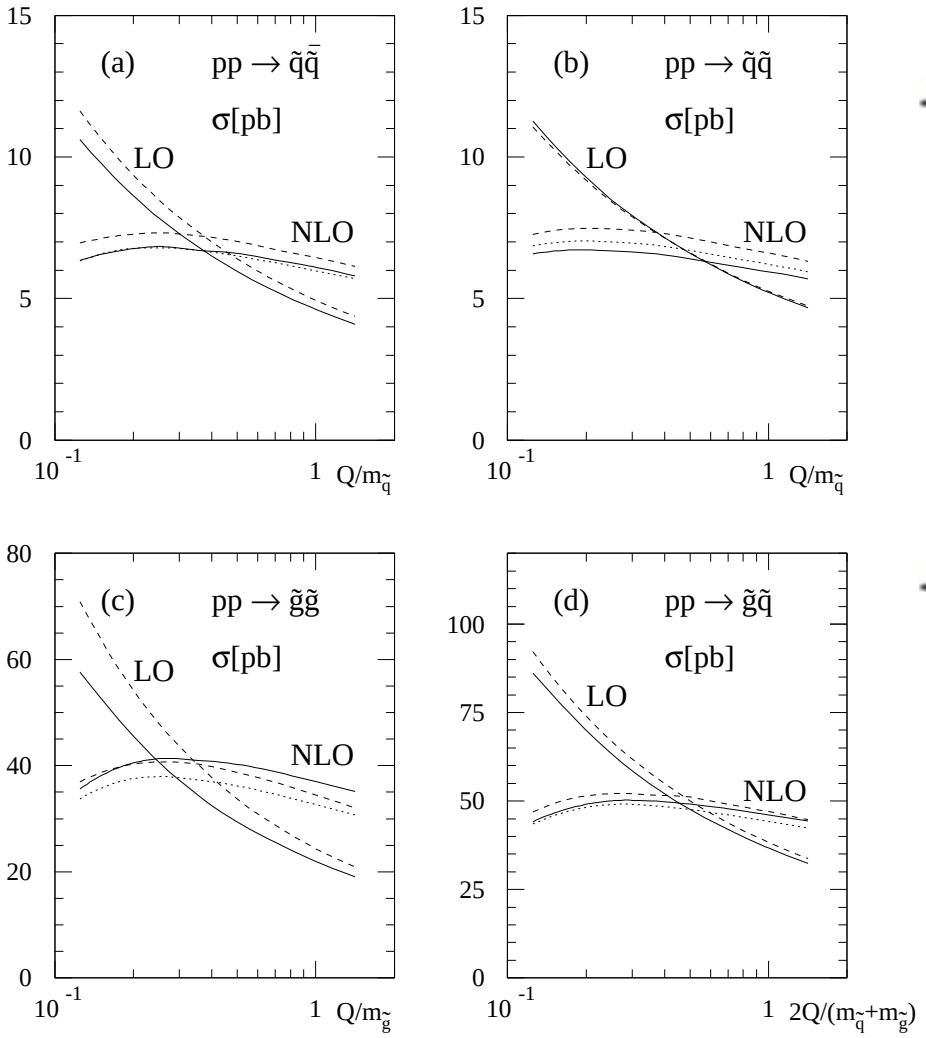
Squarks and Gluinos



- QCD corrections to squark and gluino production at LHC
  Beenakker, Höpker, Spira, Zerwas ‘96
  - essential to control theory uncertainties
  - generally sizeable K-factors at NLO of $\mathcal{O}(30\% - 40\%)$
  - increase discovery potential
- Plot (left): renormalization scale dependence of total cross section for $m_t = 175\text{GeV}$, $m_{\tilde{q}} = 600\text{GeV}$, $m_{\tilde{g}} = 500\text{GeV}$ and different PDFs

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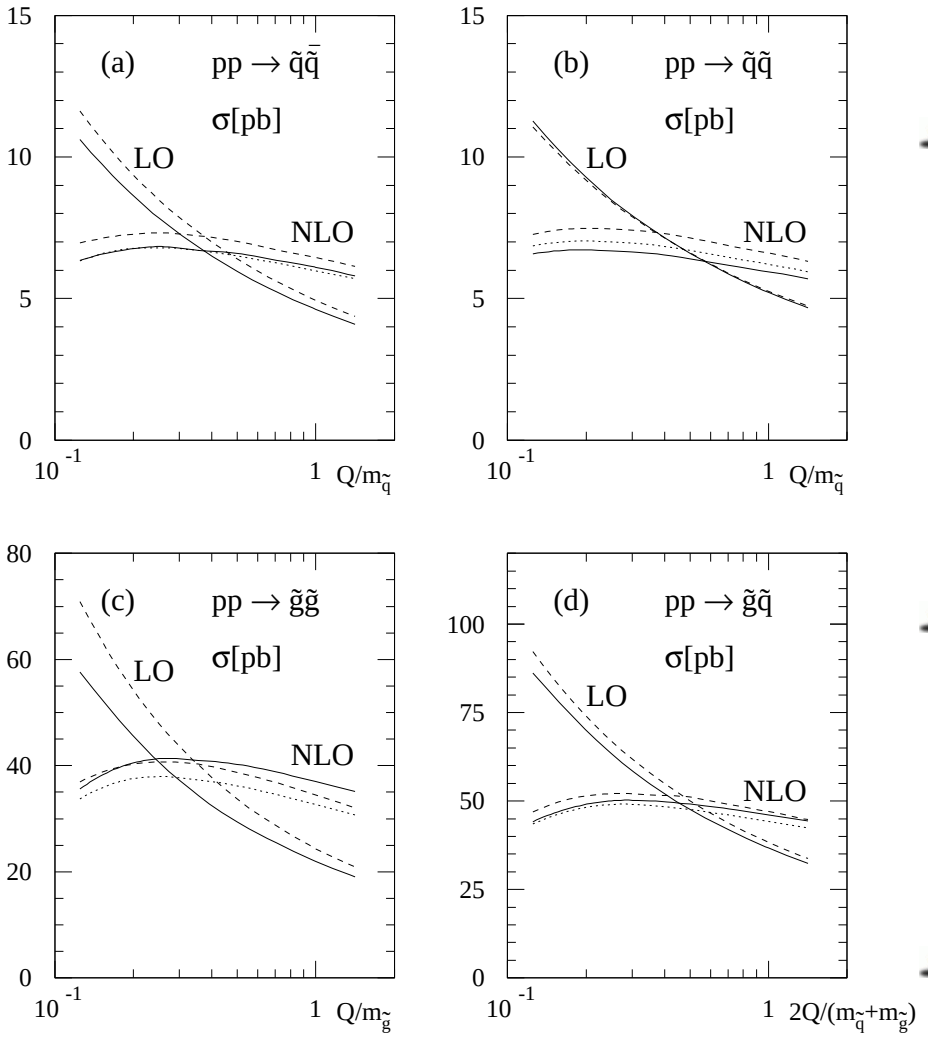

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- Further topics

  CERN/DESY Workshop HERA and the LHC '04-'06; `www.desy.de/heralhc`

  Fermilab/CERN Workshop TeV4LHC '05-'06; `www.fnal.gov/tev4lhc`