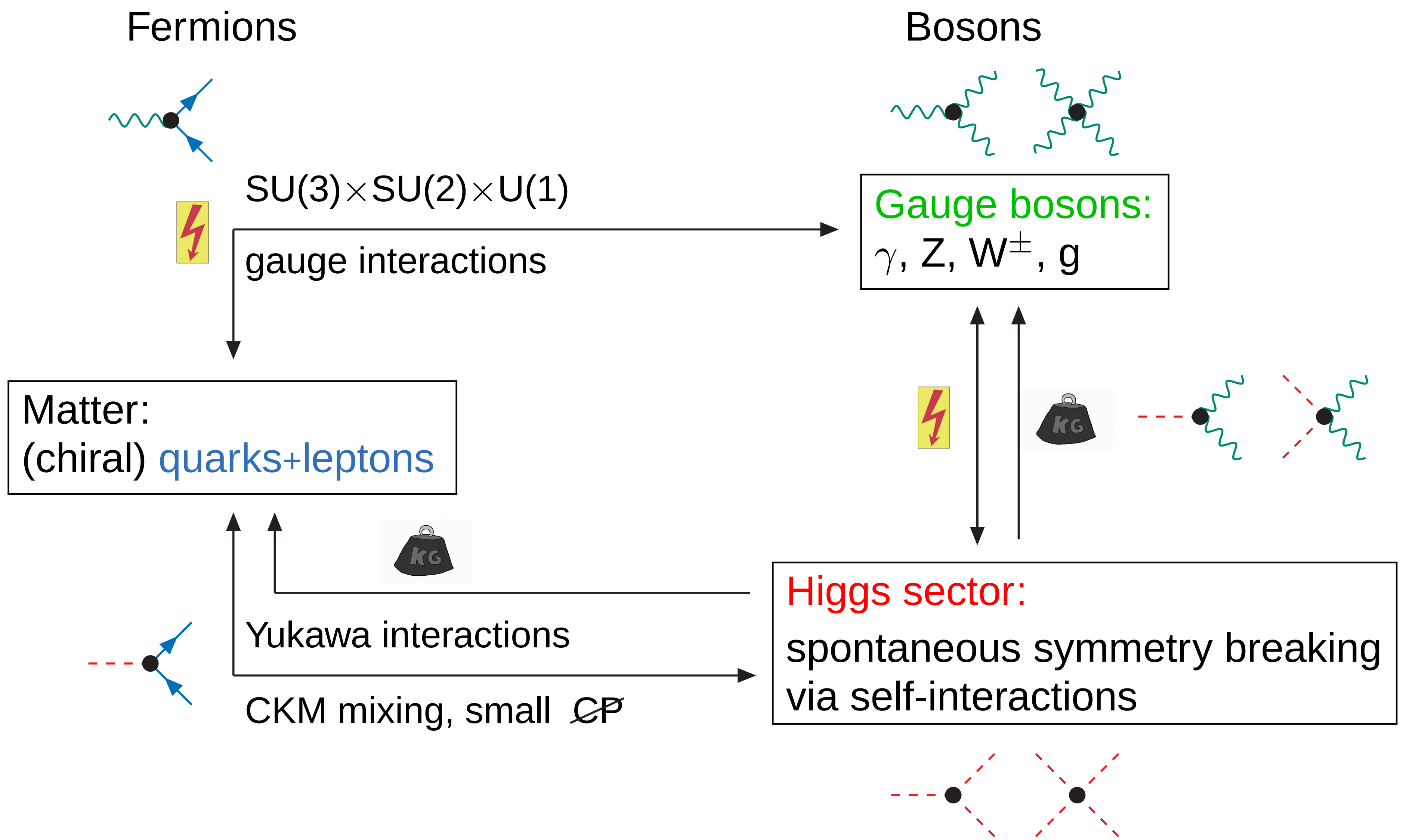
Predicting signal and background for ttH production at the LHC

Stefan Dittmaier
Albert-Ludwigs-Universität Freiburg

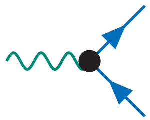
Contents

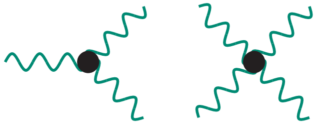
Introduction

Structure and elementary interactions of the SM



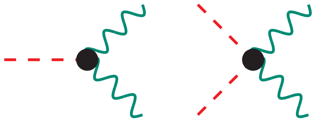
Structure and elementary interactions of the SM

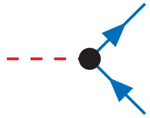




Test of the model

$\Leftrightarrow$ Exp. reconstruction of the $\underbrace{\text{elementary couplings}}_{\text{Feynman rules}}$





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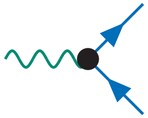
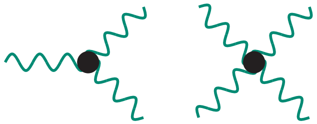


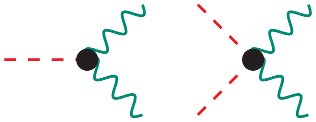


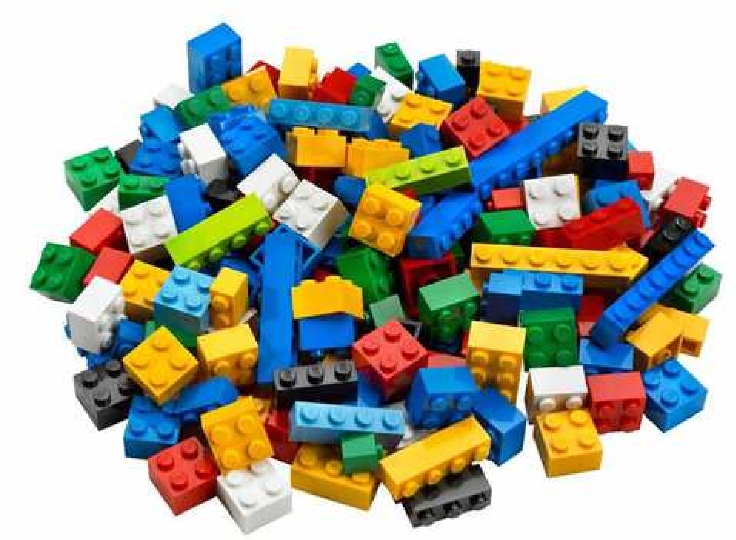
Test of the model

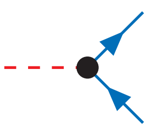
$\Leftrightarrow$ Exp. reconstruction of the elementary couplings

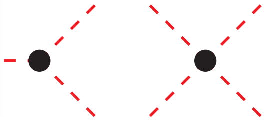
Feynman rules

Building blocks for particle reactions

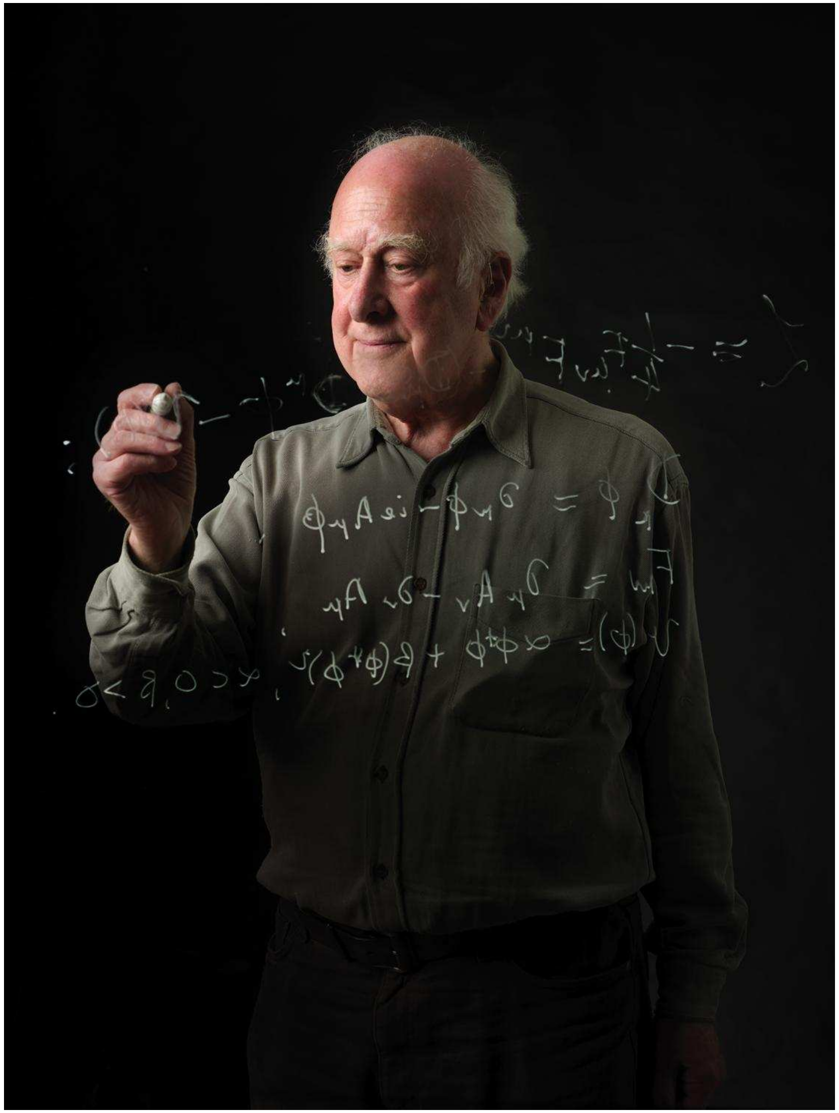








The Higgs mechanism – how do particles get their mass ?



Peter Higgs

... describing the Abelian Higgs model

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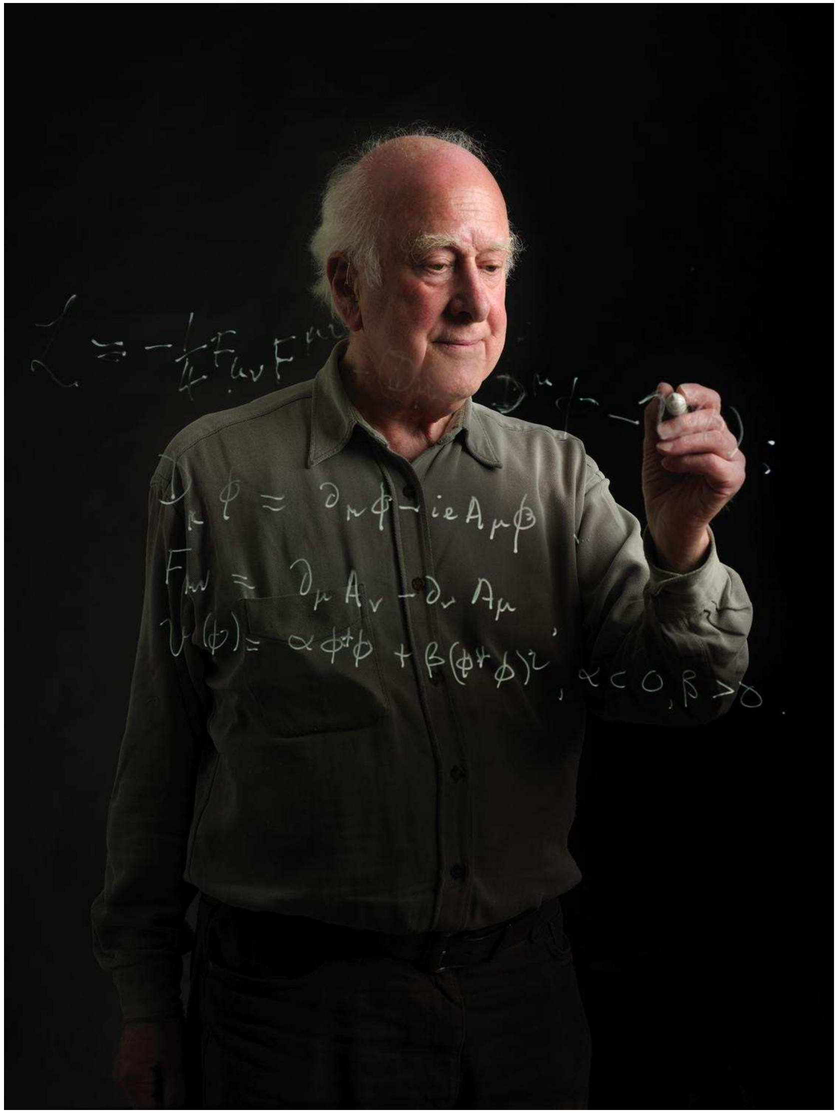

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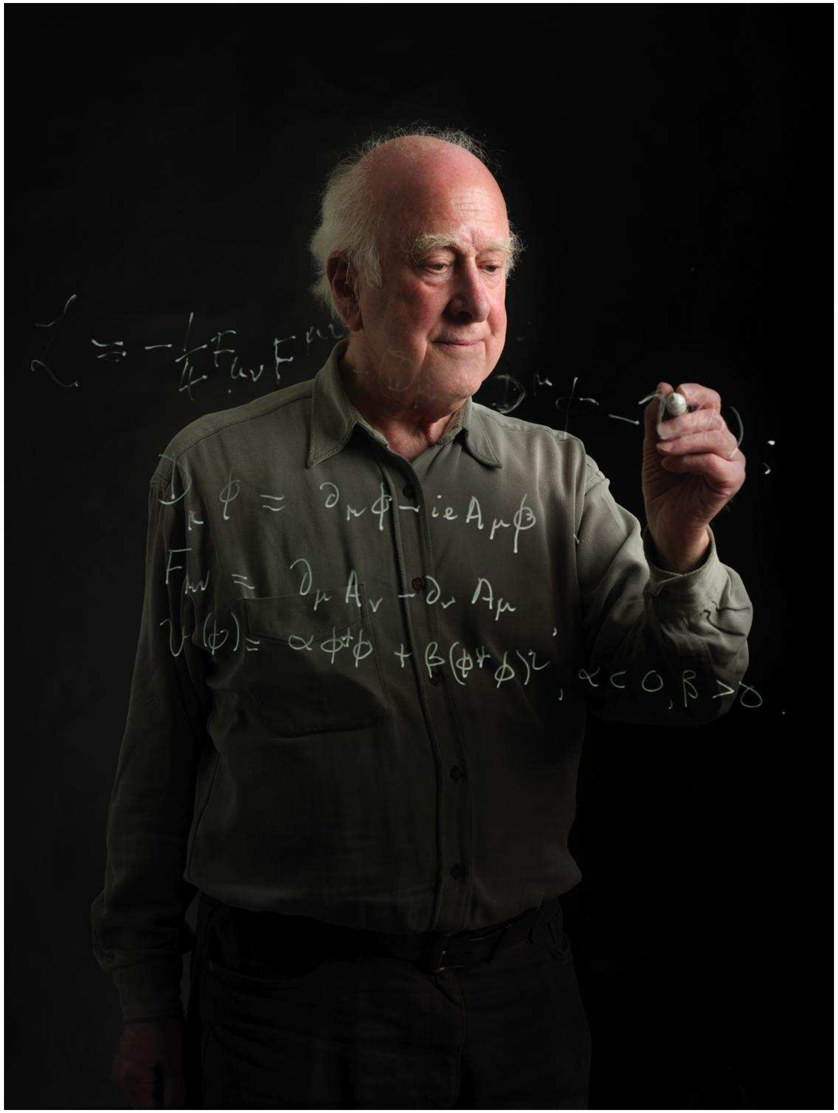

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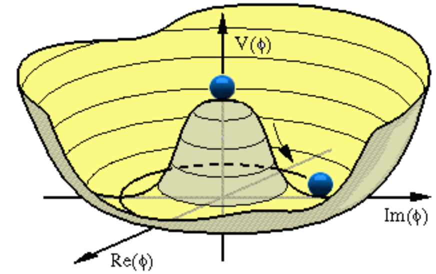
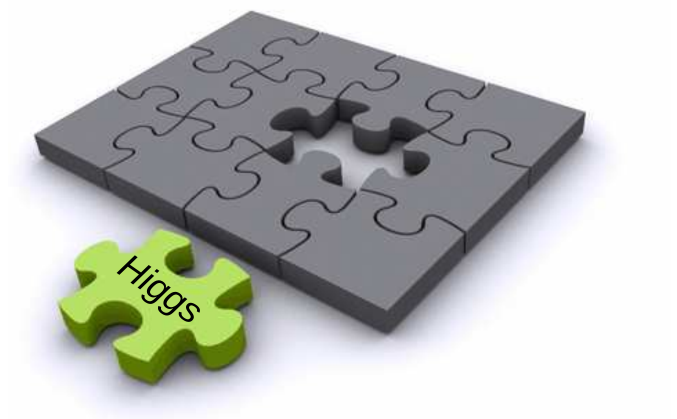


- Vacuum configuration $\langle 0|\phi(x)|0\rangle \neq 0$
  determined by minimum of potential
  $\hookrightarrow$ $\langle 0|\phi(x)|0\rangle = v$ not invariant,
  i.e. spontaneous symmetry breaking
- field excitation: $H =$ Higgs boson
  $\phi(x) = v + H(x) + \mathrm{i}\chi(x)$
- coupling of field ψ to ϕ:
  $$g\phi(x)\psi(x)^2 = \underbrace{gv}_{=m}\,\psi(x)^2 + gH(x)\psi(x)^2 + \dots$$

$\hookrightarrow$ ψ gets mass $m = vg$

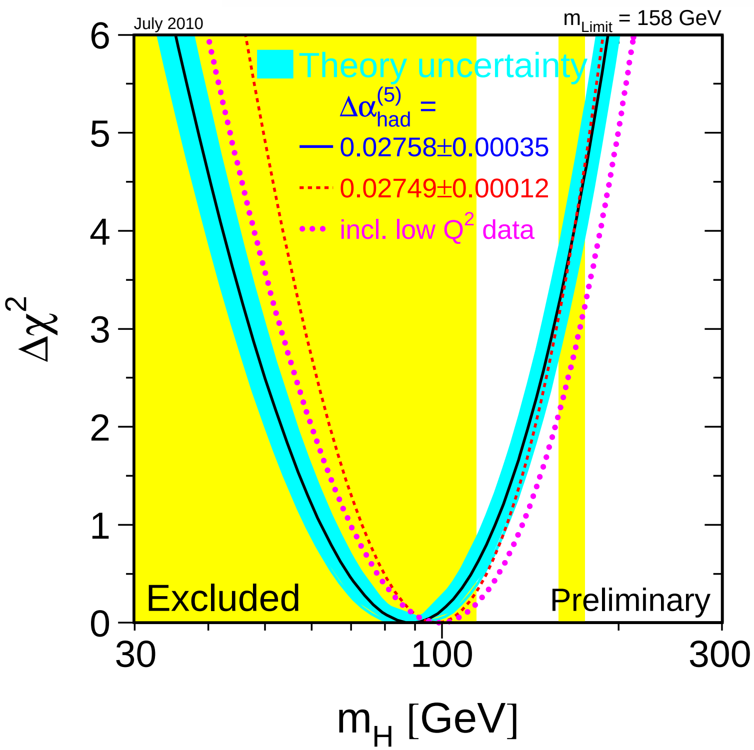
Central results from LEP/SLC/Tevatron

- Confirmation of the Standard Model as quantum field theory (quantum corrections significant)
- Particle content completely discovered apart from Higgs boson
- Higgs mass M_{H} indirectly constrained
  $\hookrightarrow$ impact on Higgs search

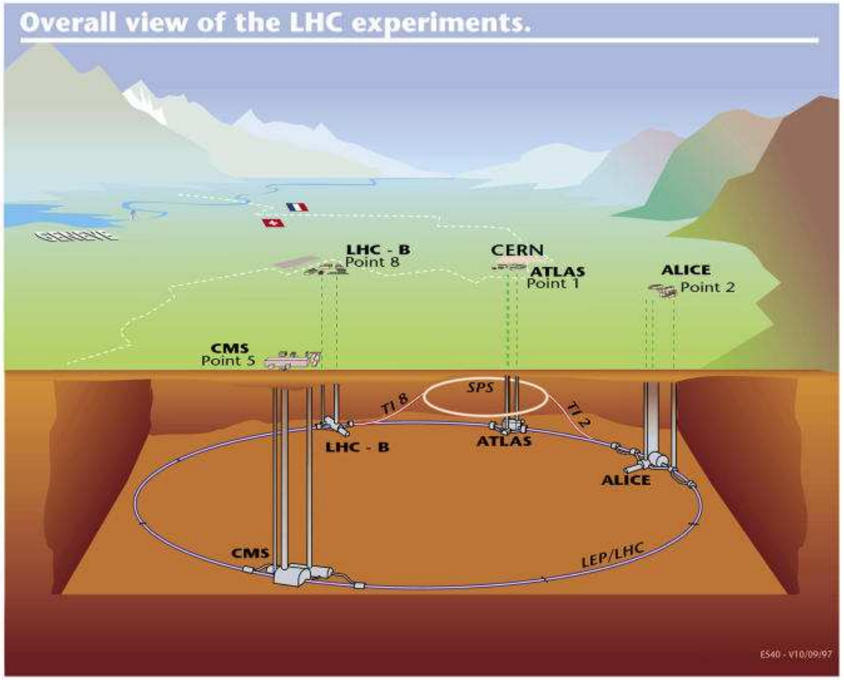


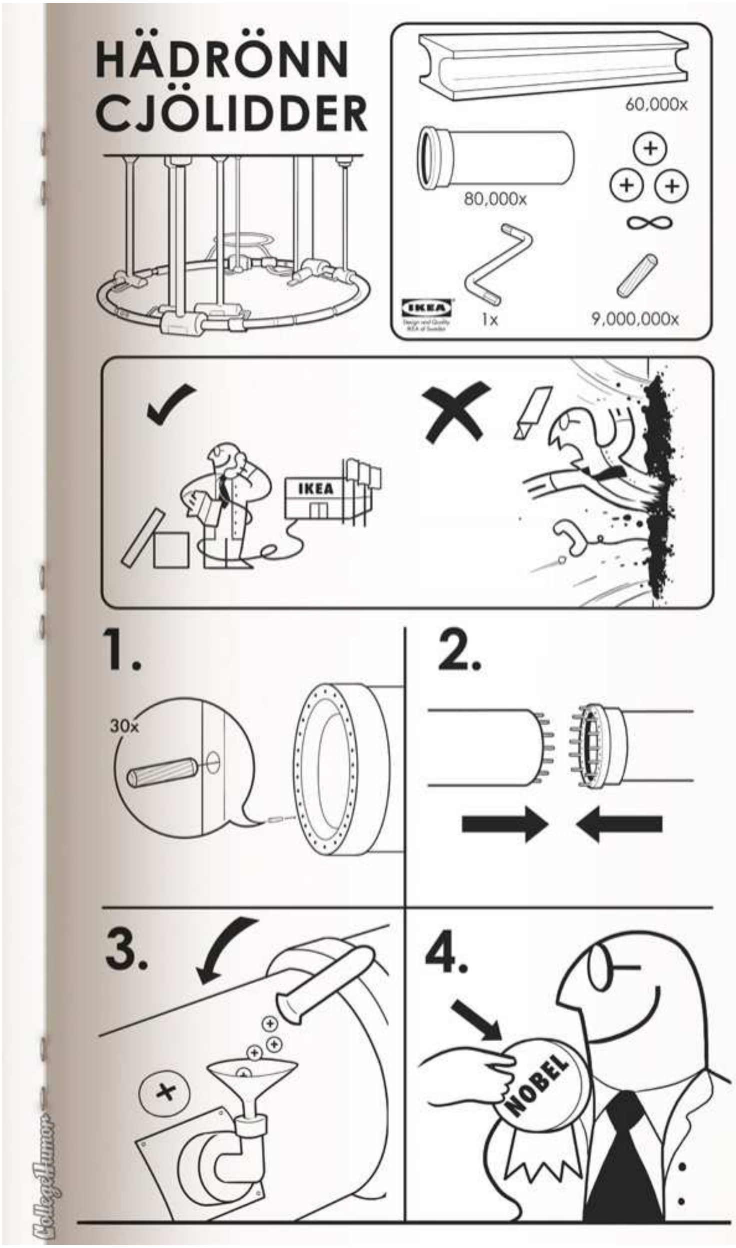
Great success of electroweak precision physics

- $M_{\mathrm{H}} > 114.4\,\mathrm{GeV}$ (LEPHIGGS '02)
  $\mathrm{e^+e^-} \not\to \mathrm{ZH}$ at LEP2
- $M_{\mathrm{H}} < 158\,\mathrm{GeV}$ or $M_{\mathrm{H}} > 175\,\mathrm{GeV}$
  $\mathrm{p\bar{p}} \not\to \mathrm{H} \to \mathrm{WW}$ at Tevatron (CDF/D0 '10)
- $M_{\mathrm{H}} < 158\,\mathrm{GeV}$ (LEPEWWG '10)
  fit to precision data
  i.e. via quantum corrections



Large Hadron Collider – the world largest particle accelerator

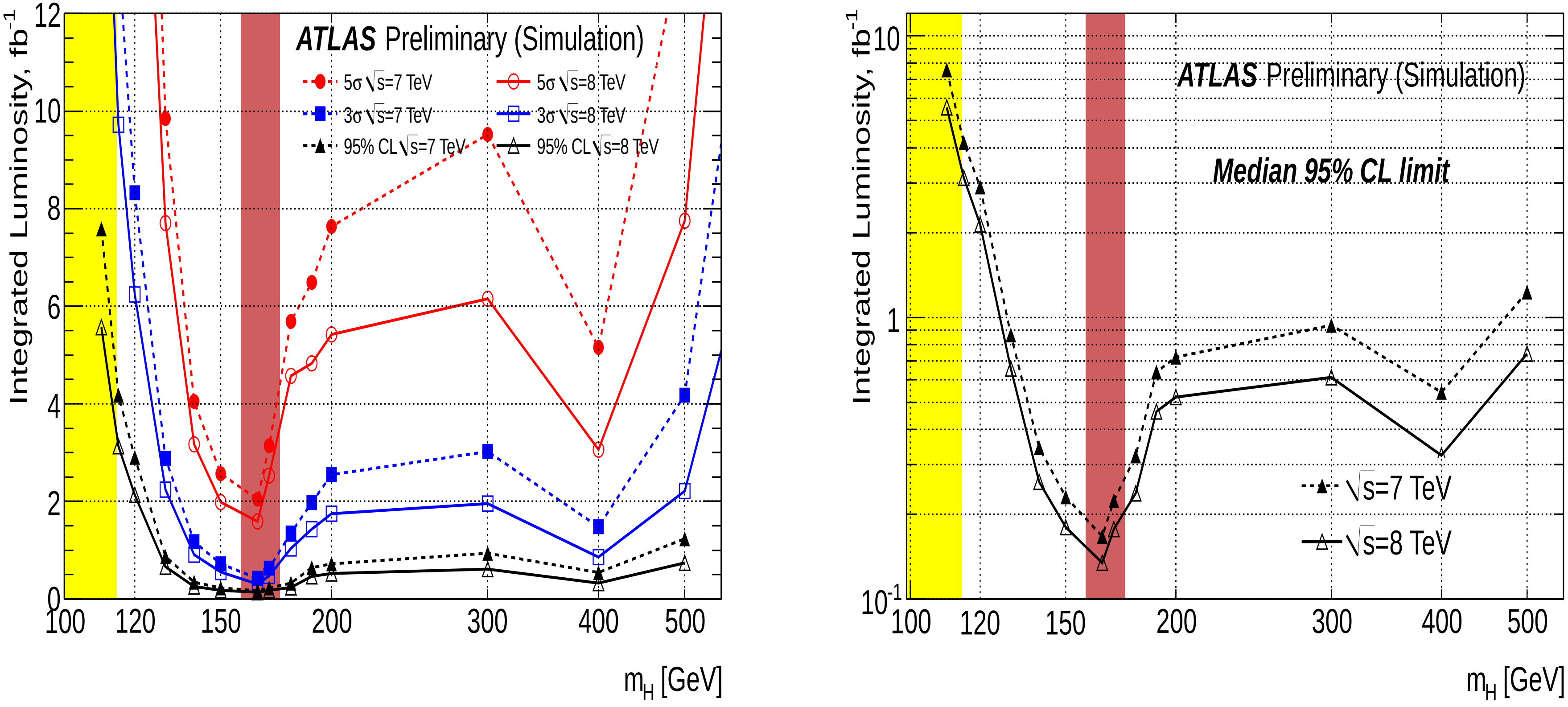




- 30.03.10: LHC turns to $E_{\mathrm{CM}} = 7\,\mathrm{TeV}$
  - $\hookrightarrow$ $\mathcal{L} \sim 45\,\mathrm{pb}^{-1}$ each at ATLAS/CMS
  - $\hookrightarrow$ rediscovery of SM physics (W's, Z's, $\mathrm{t\bar{t}}$, etc.)
- 2011/12: run at $7\,\mathrm{TeV}$
  - $\hookrightarrow$ collect luminosity of some fb^{-1}
- 2013: shutdown and upgrade
- 2014: run at $E_{\mathrm{CM}} = 14\,\mathrm{TeV}$
  - $\hookrightarrow$ collect some $10^3\,\mathrm{fb}^{-1}$ until end (?)

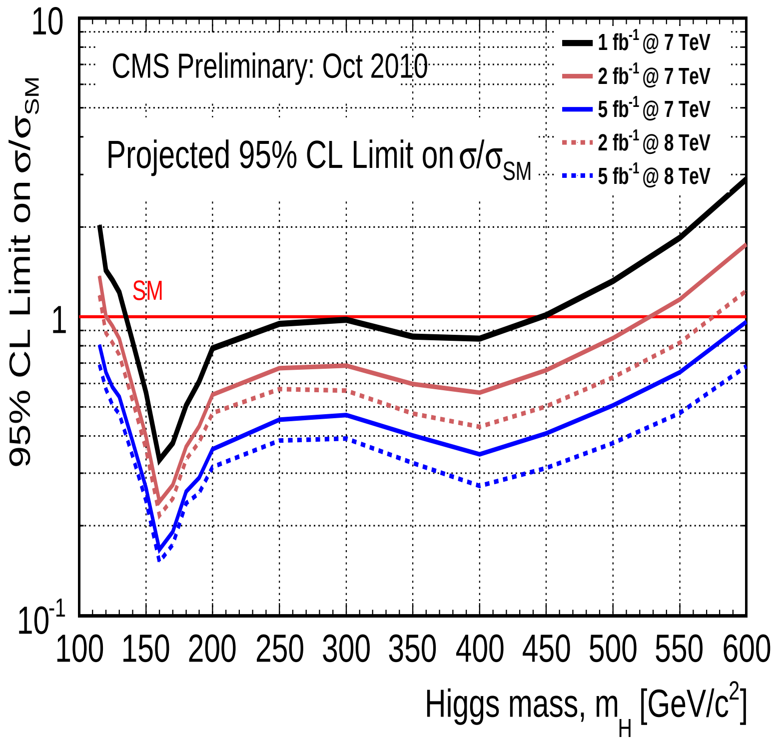
Prospects for the Higgs search at $7\,\mathrm{TeV}$

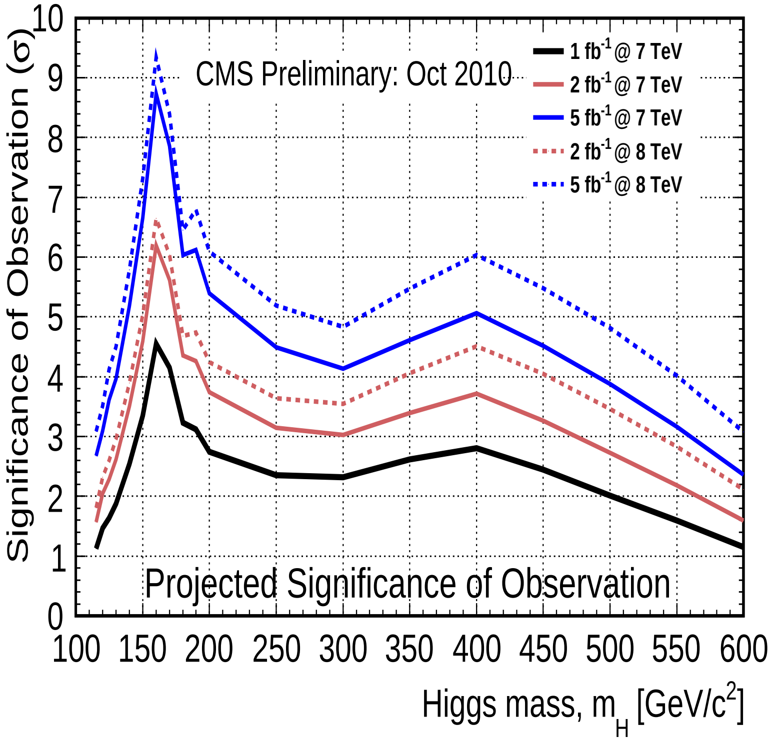
Required luminosity required for 95% CL exclusion, 3σ evidence, or 5σ discovery:



Prospects for the Higgs search at $7\,\mathrm{TeV}$ (continued)

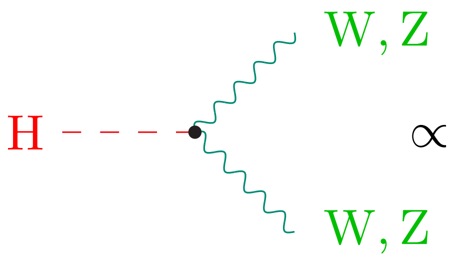
Exclusion and discovery prospects for different scenarios:



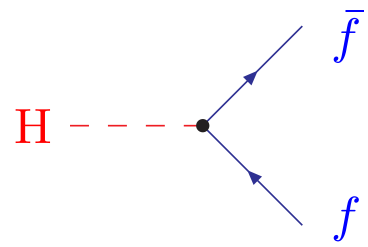


Higgs search at the LHC

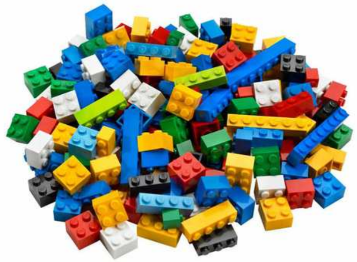
Higgs bosons couple proportional to particle masses:



$\propto M_{\mathrm{W}}$



$\propto m_f$



$\Rightarrow$ Higgs production via couplings to W/Z bosons or top-quarks

Higgs search at the LHC

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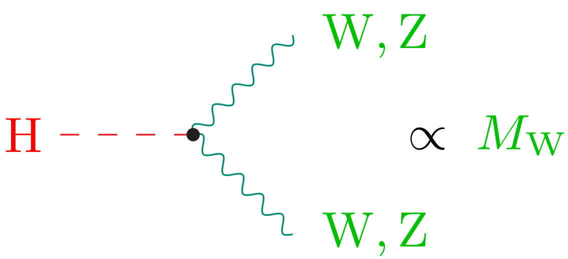
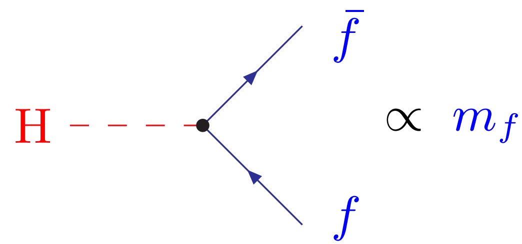
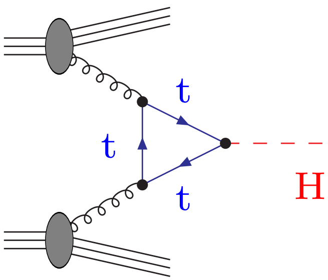
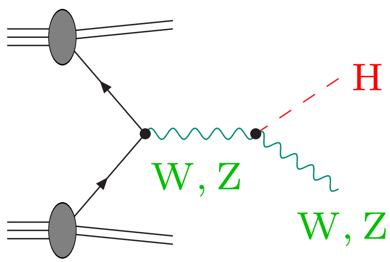


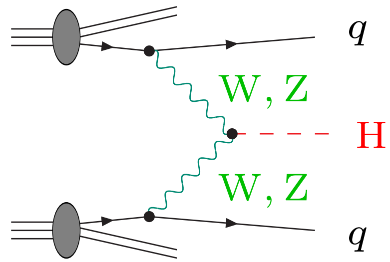


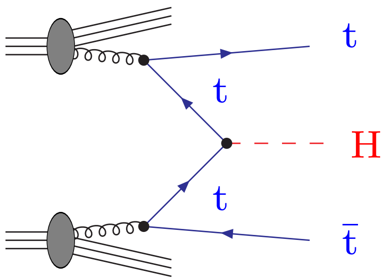
$\Rightarrow$ Higgs production via couplings to W/Z bosons or top-quarks

Processes at hadron colliders ($\mathrm{p\bar{p}/pp}$):









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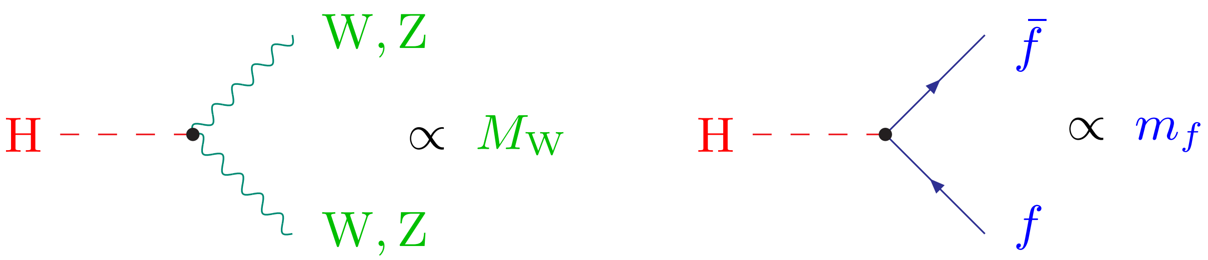
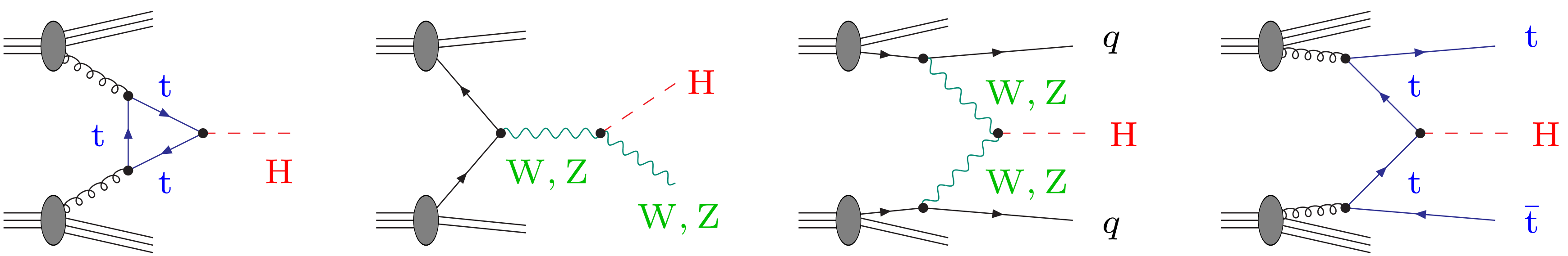
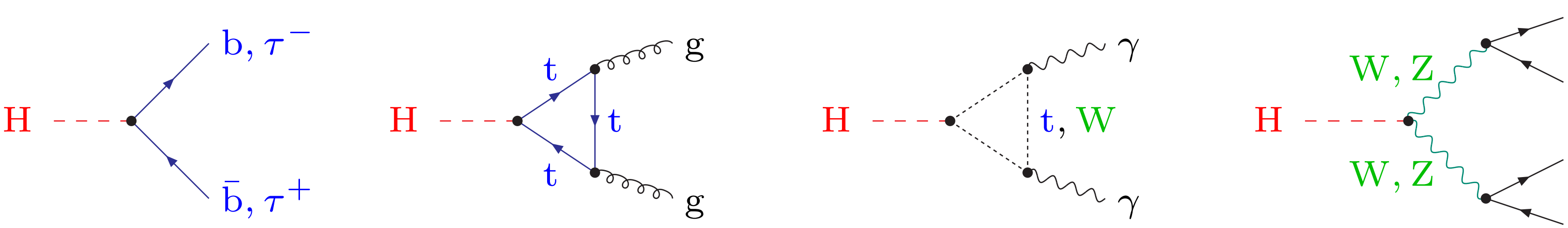


⇒ Higgs production via couplings to W/Z bosons or top-quarks

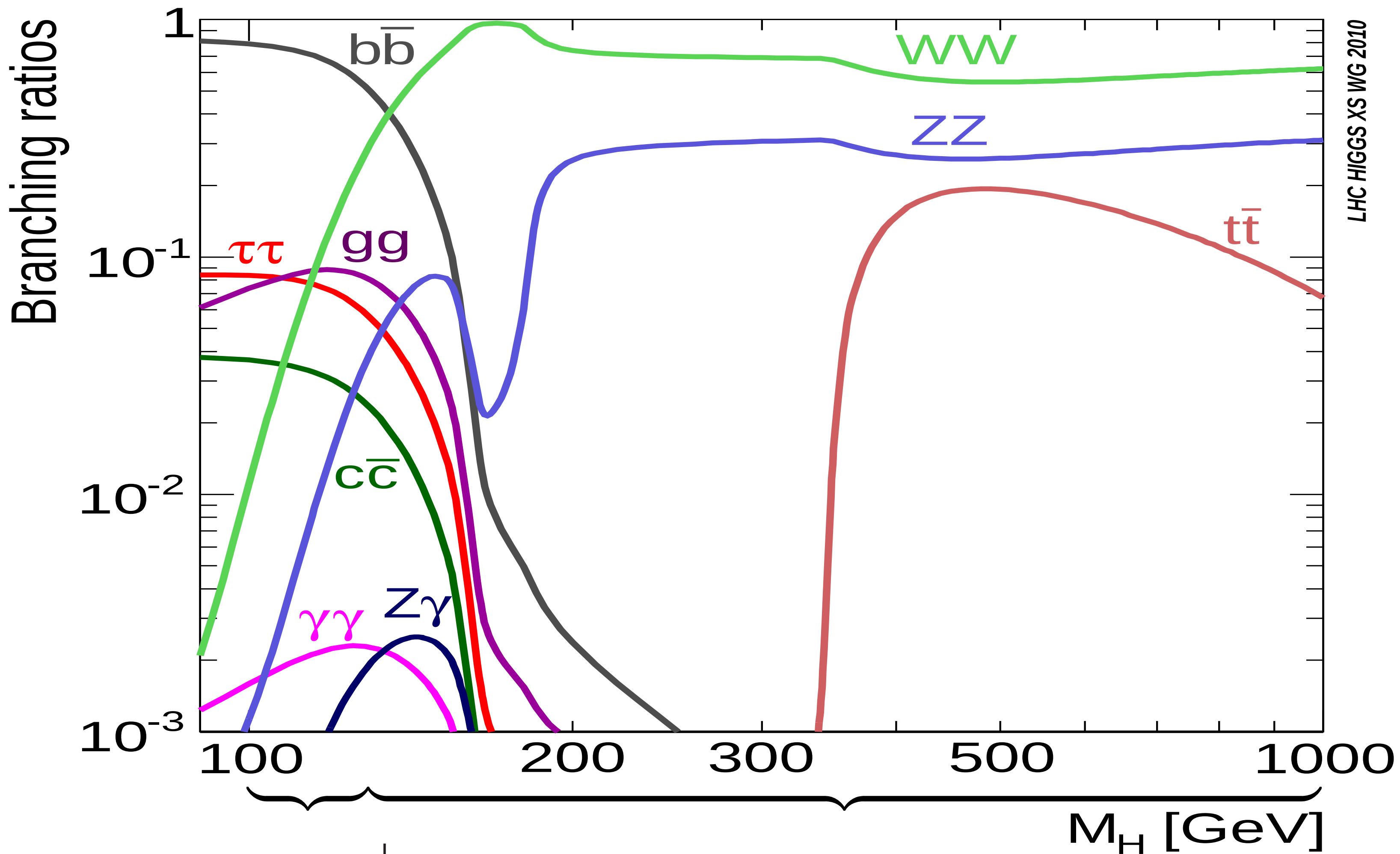
Processes at hadron colliders ($\mathrm{p\bar{p}/pp}$):



Decay channels for Higgs bosons of moderate mass ($M_H \lesssim 300\,\mathrm{GeV}$):



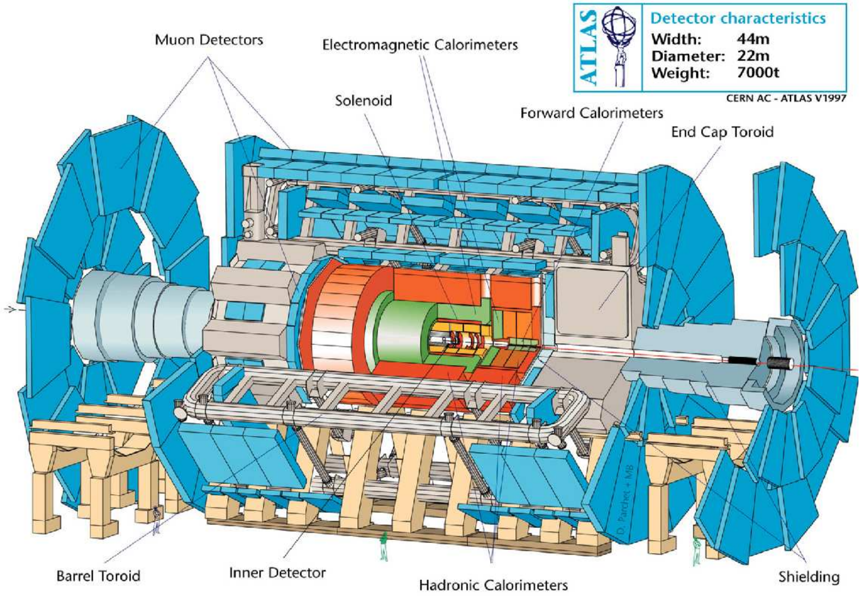
Branching ratios of the SM Higgs boson

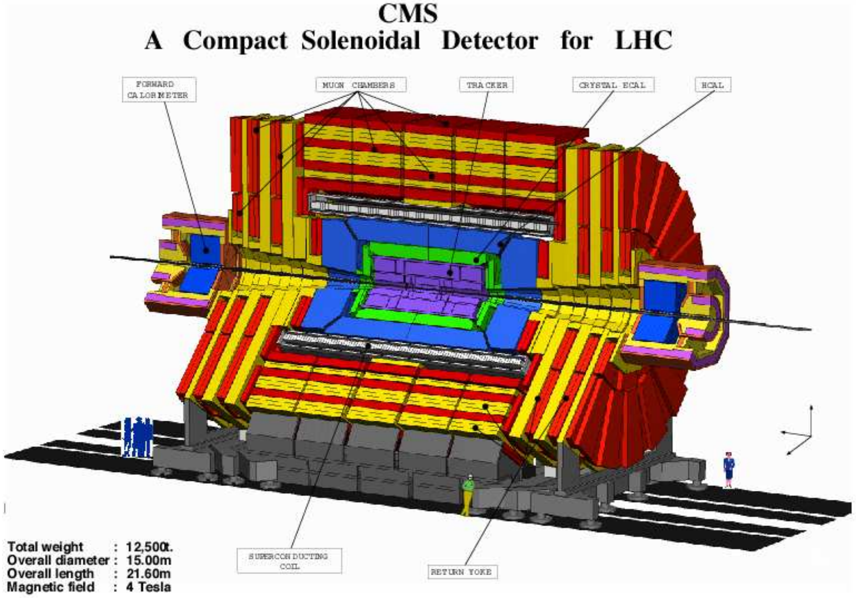


experimentally difficult:
$\mathrm{b\bar{b}}$ with large background,
decays into $\gamma\gamma$, $\tau\tau$ rare

experimentally clear signals by
$\mathrm{H \to WW \to 2}$ leptons $+ 2$ neutrinos or
$\mathrm{H \to ZZ \to 4}$ leptons

Higgs event reconstruction with detectors ATLAS and CMS





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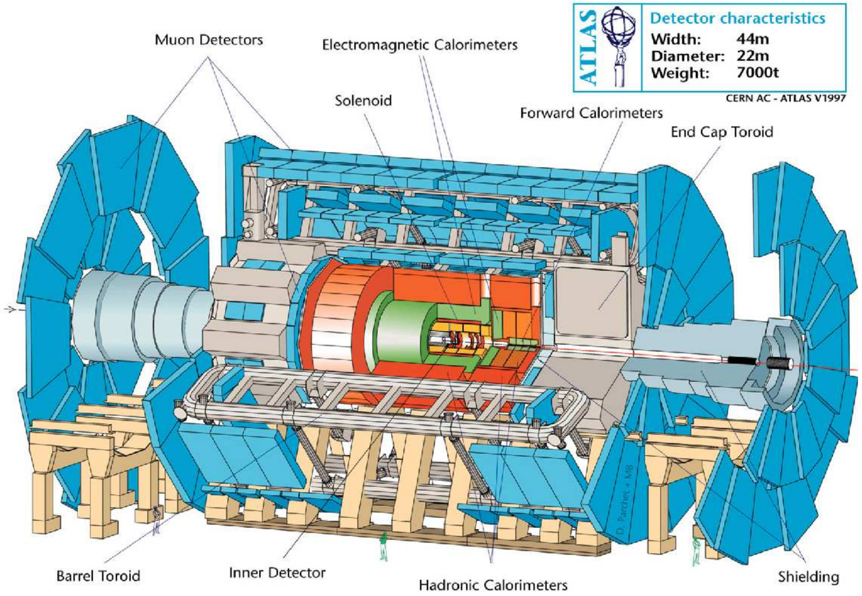
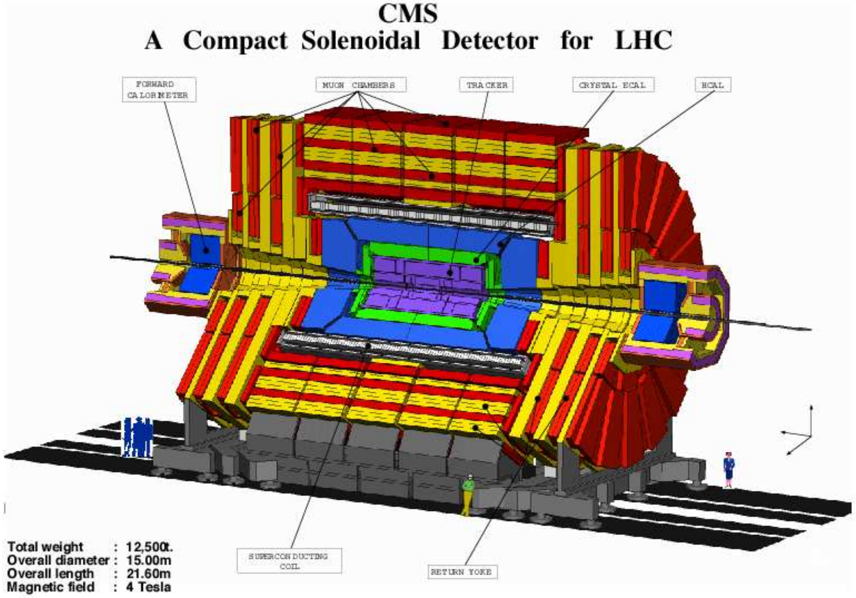
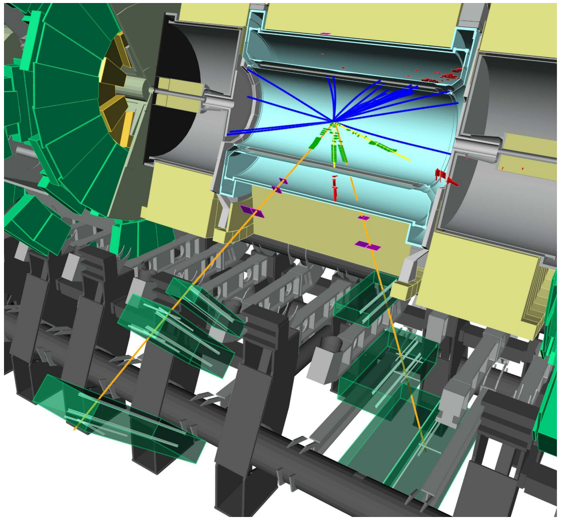
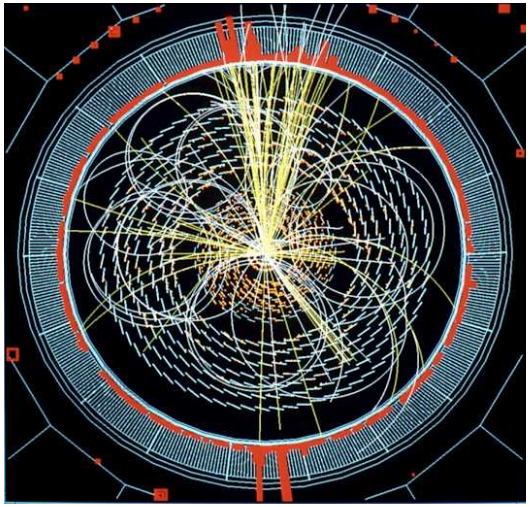




Simulation of Higgs events

("'simple"' signatures $\mathrm{H} \to \mathrm{ZZ} \to 2\mathrm{e}2\mu/2\mathrm{e}2q$)





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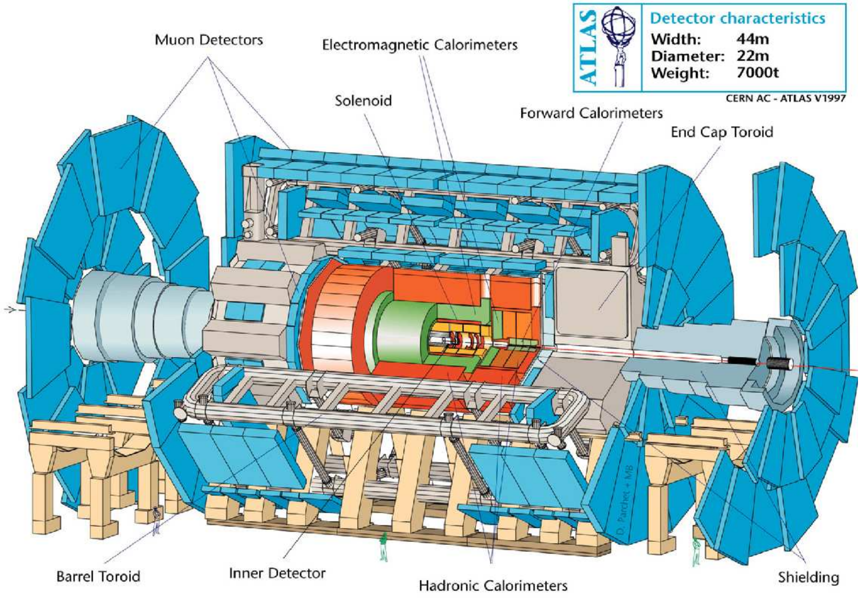

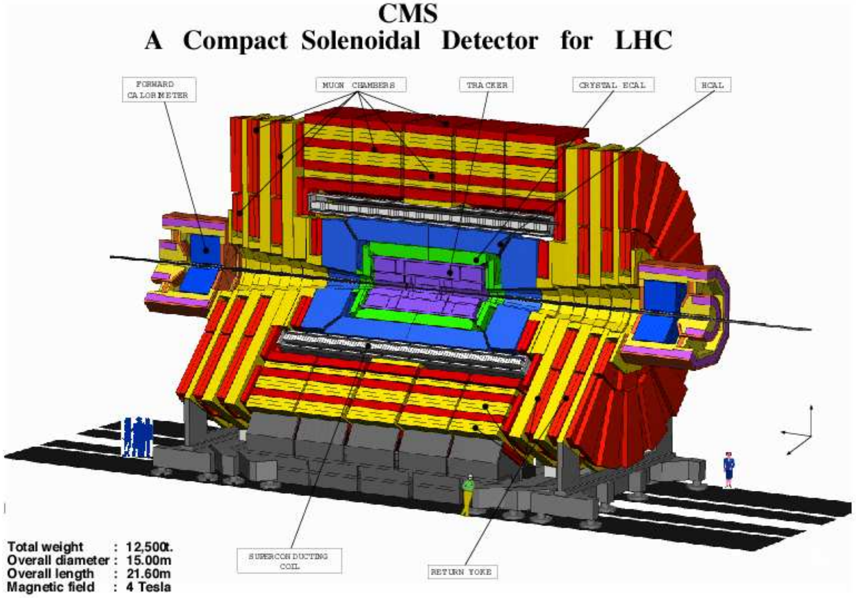

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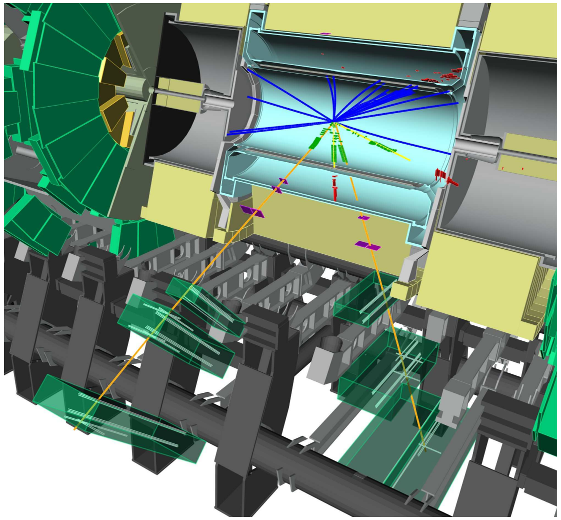
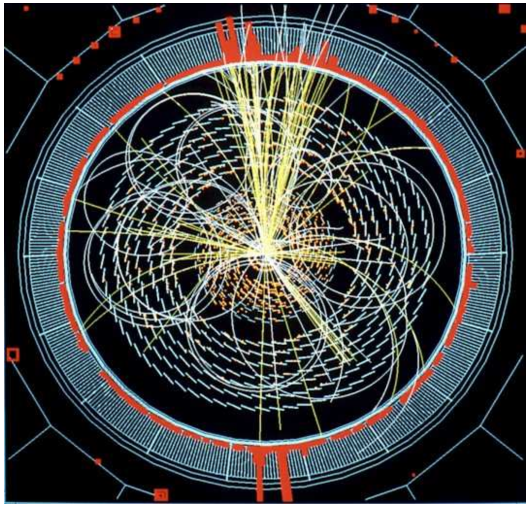
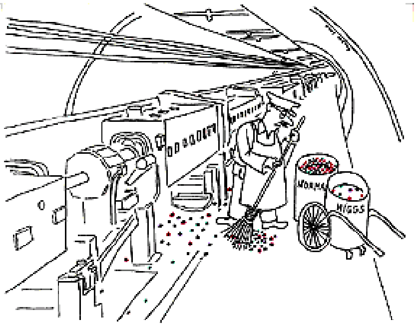




Precise predictions necessary, otherwise …



LHC-Higgs cross section group → mandate for theory update

CrossSections < LHCPhysics < TWiki - Mozilla Firefox

Datei Bearbeiten Ansicht Chronik Lesezeichen Extras Hilfe

https://twiki.cern.ch/twiki/bin/view/LHCPhysics/CrossSections

Meistbesuchte Se... Getting Started Latest Headlines

(22-28 July 2010) | Indico - Management area | CrossSections < LHCPhysics...

Organization

Overall Contacts

ATLAS	CMS	THEORY	
Reisaburo Tanaka (LAL)	Chiara Mariotti (Torino)	Stefan Dittmaier (Freiburg)	Giampiero Passarino (Torino)

Subgroup Contacts and Link for Subgroup Wiki

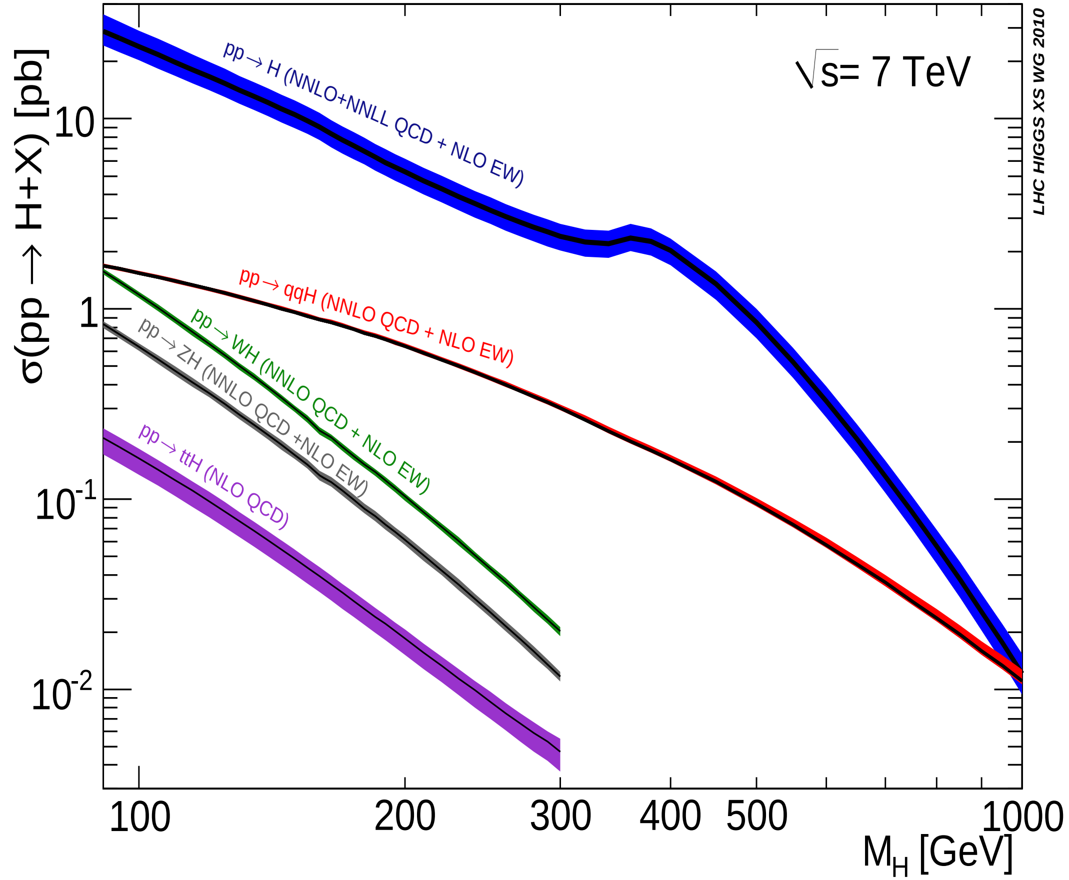
* We are organized in 10 subgroups, with 2 experimental contacts (one from ATLAS and one from CMS) and 2 theoretical contacts.

* LHCb collaboration participates in WH/ZH group.

Group	ATLAS	CMS	LHCb	THEORY	
1. *ggF*	Jianming Qian (Michigan)	Fabian Stöckli (CERN)		Massimiliano Grazzini (Firenze)	Frank Petriello (Wisconsin)
2. *VBF*	Daniela Rebuzzi (Pavia) Sinead Farrington (Oxford)	Christoph Hackstein (Karlsruhe)		Ansgar Denner (PSI)	Carlo Oleari (Milano-Bicocca)
3. *WH/ZH*	Giacinto Piacquadio (CERN)	Jim Olsen (Princeton)	Clara Matteuzzi (Milano-Bicocca)	Stefan Dittmaier (Freiburg)	Robert Harlander (Wuppertal)
4. *ttH*	Simon Dean (UCL)	Chris Neu (Virginia)		Laura Reina (Florida)	Michael Spira (PSI)
5. *MSSM neutral*	Markus Warsinsky (Freiburg)	Monica Vazquez Acosta (IC)		Michael Spira (PSI)	Georg Weiglein (DESY)
6. *MSSM charged*	Martin Flechl (Freiburg)	Sami Lehti (Helsinki)		Michael Krämer (Aachen)	Tilman Plehn (Heidelberg)
7. *PDF*	Joey Huston (Michigan State)	Kajari Mazumdar (TIFR)		Stefano Forte (Milano)	Robert Thorne (UCL)
8. *Branching ratios*	Daniela Rebuzzi (Pavia)	Ivica Puljak (Split)		Ansgar Denner (PSI)	Sven Heinemeyer (IFCA)
9. *NLO MC*	Jae Yu (Texas)	Marta Felcini (UCD)		Fabio Maltoni (Louvain)	Paolo Nason (Milano-Bicocca)
10. *Pseudo-observables*	Michael Dührssen (CERN)	Martin Grünewald (Ghent)		Sven Heinemeyer (IFCA)	Giampiero Passarino (Torino)

Fertig twiki.cern.ch

Updated SM Higgs XS predictions for the LHC at $\sqrt{s} = 7\,\mathrm{TeV}$

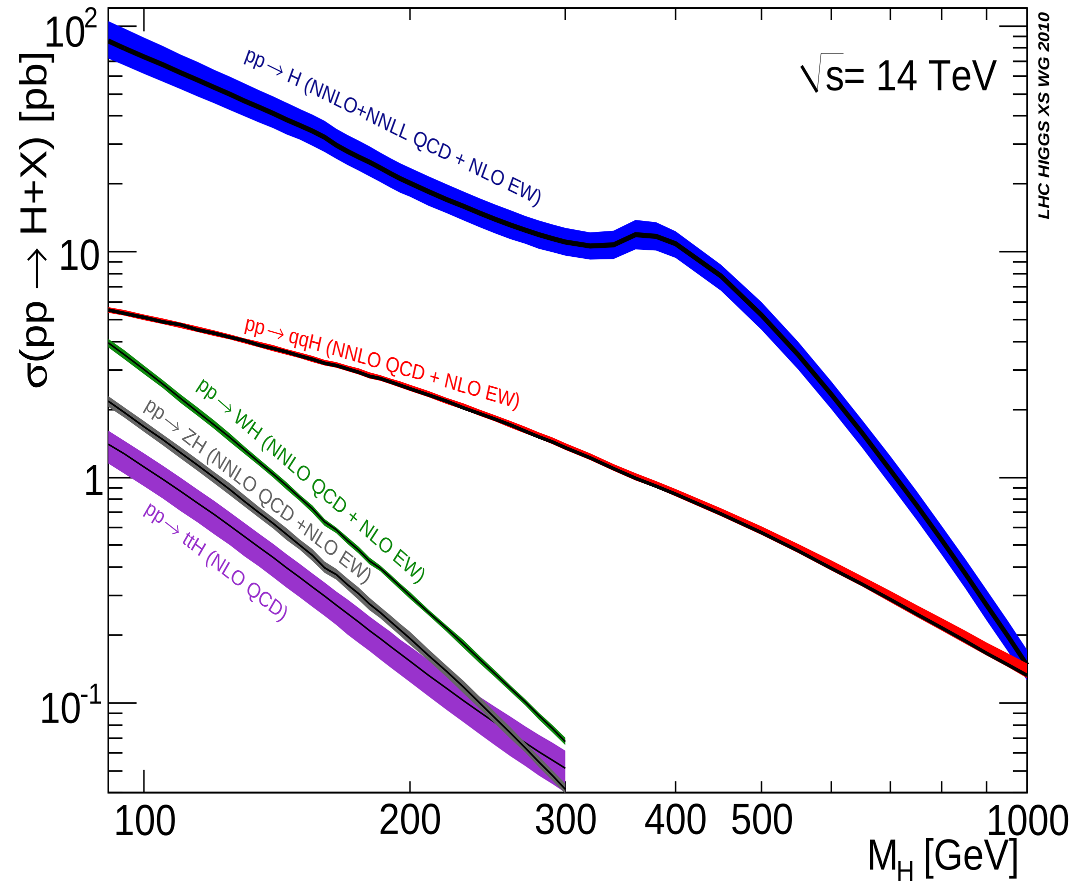


Rough numbers:

	M_{H}	Uncertainties scale	Uncertainties PDF4LHC	NLO/NNLO/NNLO+ QCD	NLO/NNLO/NNLO+ EW
ggF	$< 500\,\mathrm{GeV}$	$6-10\%$	$8-10\%$	$>100\%$	5%
VBF	$< 500\,\mathrm{GeV}$	1%	$2-7\%$	5%	5%
WH	$< 200\,\mathrm{GeV}$	1%	$3-4\%$	30%	$5-10\%$
ZH	$< 200\,\mathrm{GeV}$	$1-2\%$	$3-4\%$	40%	5%
ttH	$< 200\,\mathrm{GeV}$	10%	9%	5%	?

LHC Higgs XS WG '10

Updated SM Higgs XS predictions for the LHC at $\sqrt{s} = 14\,\mathrm{TeV}$



Rough numbers:

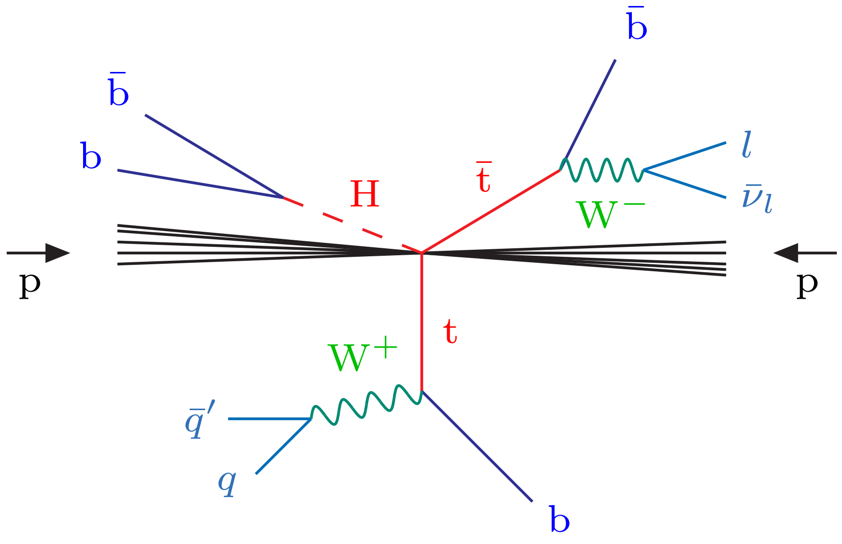
	M_{H}	Uncertainties scale	PDF4LHC	NLO/NNLO/NNLO+ QCD	EW
ggF	$< 500\,\mathrm{GeV}$	$6-14\%$	7%	$>100\%$	5%
VBF	$< 500\,\mathrm{GeV}$	1%	$3-4\%$	5%	5%
WH	$< 200\,\mathrm{GeV}$	1%	$3-4\%$	30%	$5-10\%$
ZH	$< 200\,\mathrm{GeV}$	$2-4\%$	$3-4\%$	45%	5%
ttH	$< 200\,\mathrm{GeV}$	10%	9%	$15-20\%$	?

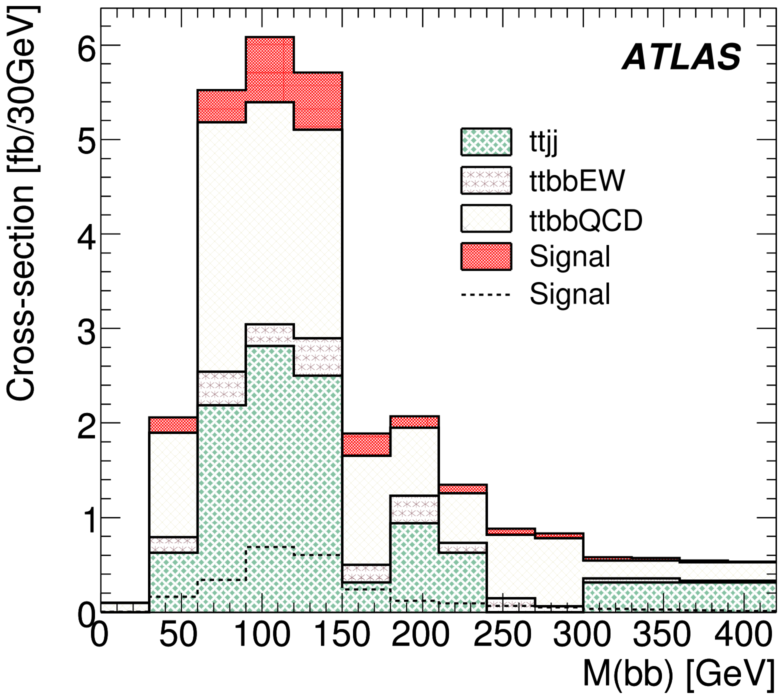
LHC Higgs XS WG '10

Production of ttH final states at the LHC

$t\bar{t}H(\to b\bar{b})$ production – a problematic channel

“CSC book”,CERN-OPEN-2008-020



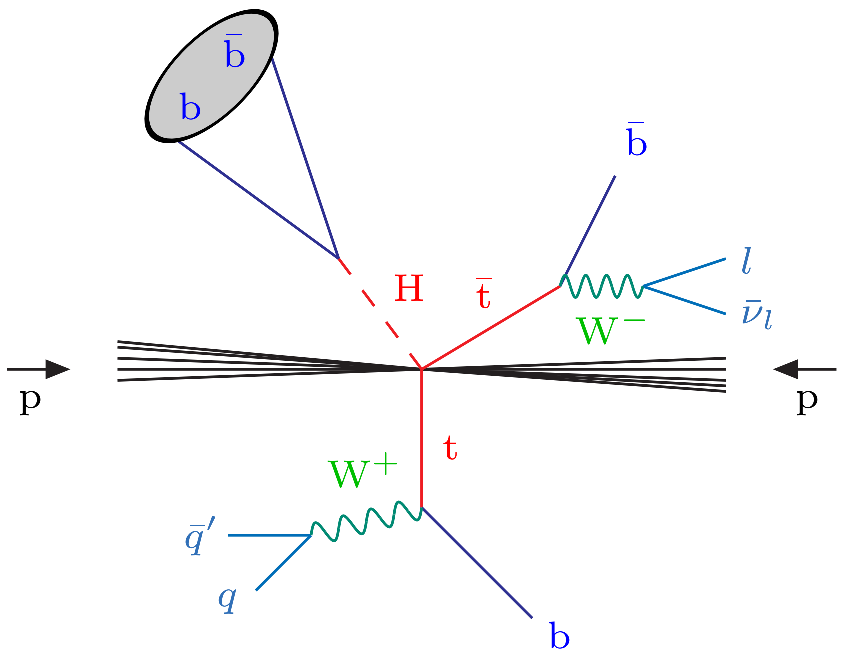


- Relevance: direct experimental access to $t\bar{t}H$ Yukawa coupling
- Problem: control background by $pp \to t\bar{t}b\bar{b}, t\bar{t} + \text{jets}$

  status 2008: signal not significant due to background contamination

  $\hookrightarrow$ activities:
  - ◇ more sophisticated tricks in analysis
  - ◇ NLO QCD prediction also for background

Idea under discussion: highly boosted “fat jets”



Butterworth et al. ’08; ATL-PHYS-PUB-2009-088

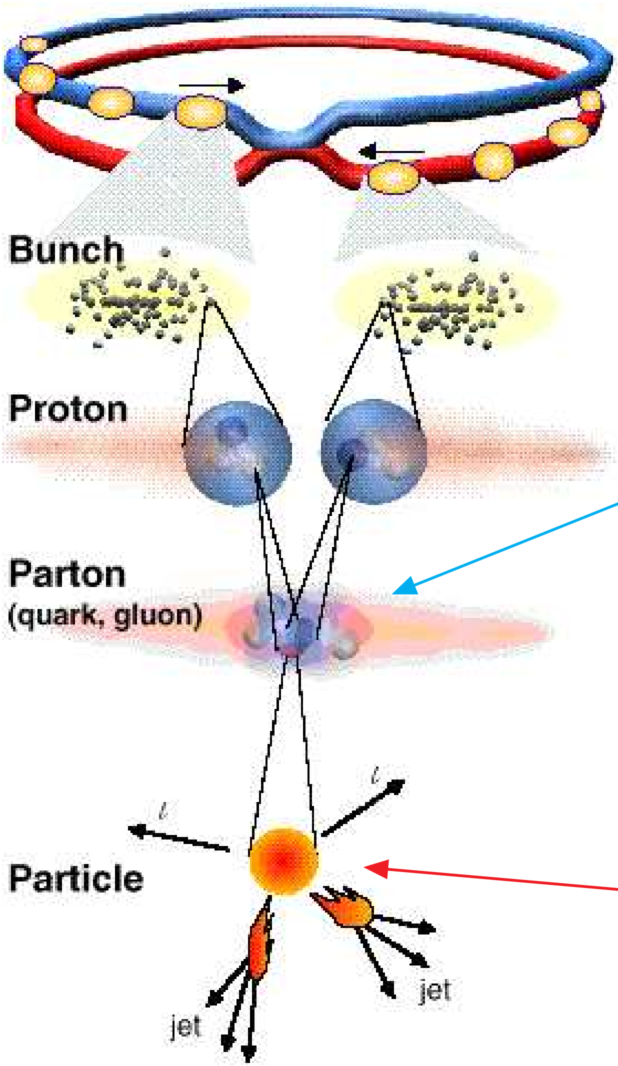
$\hookrightarrow$ fat jet containing $b\bar{b}$ pair from high-p_T Higgs (successful in WH/ZH revival!)

A theoretical study:

Plehn, Salam, Spannowsky ’09

- fat jets: $p_T > 200\,\mathrm{GeV}$ and $R = 1.5$
- substructures: $b\bar{b}$ pair with $|m_{b\bar{b}} - M_H| < 10\,\mathrm{GeV}$, similar for $t \to 3j$, etc.
- $S/\sqrt{B}$ still $\sim 2.2–2.6$ for $\mathcal{L} = 30\,\mathrm{fb}^{-1}$
- S/B raised from ~ 0.1 to $0.2–0.4$
- background mainly due to $t\bar{t}b\bar{b}$ (suppression of $t\bar{t} + 2\mathrm{jets}$)

Predicting pp collisions



Parton content of the proton:
- valence quarks uud
- sea quarks $\mathrm{u}, \mathrm{d}, \mathrm{c}, \mathrm{s}, \mathrm{b}$
- gluons g (+photons γ)

"Parton distribution functions" (PDF) $f_{i/\mathrm{p}}(x, Q)$
- determine fraction x of the p momentum
- carried by parton i at "factorization scale" Q
- = non-perturbative input (from exp.),
  but process independent

Hard interaction of partons
- $\hookrightarrow$ perturbative QFT applicable

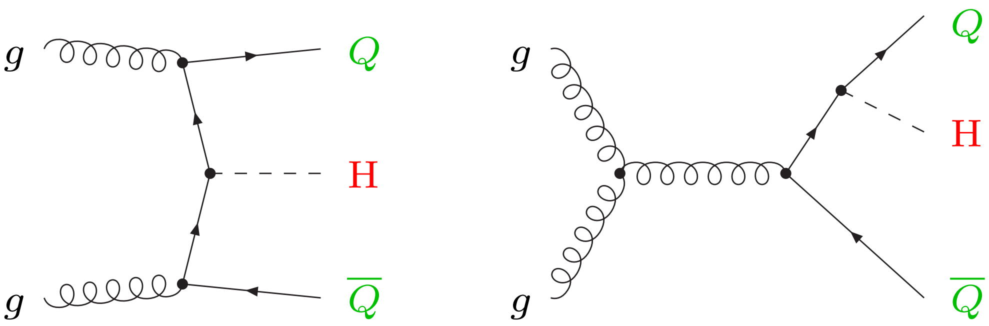
Model for hard interactions
(apart from QCD/QED) enters only here

$$\sigma_{\mathrm{pp}\to F+X}(p_1, p_2) = \int_0^1 \mathrm{d}x_a \int_0^1 \mathrm{d}x_b \sum_{a,b} f_{a/\mathrm{p}}(x_a, Q)\, f_{b/\mathrm{p}}(x_b, Q)\, \hat{\sigma}_{ab\to F}(x_a p_1, x_b p_2, Q)$$

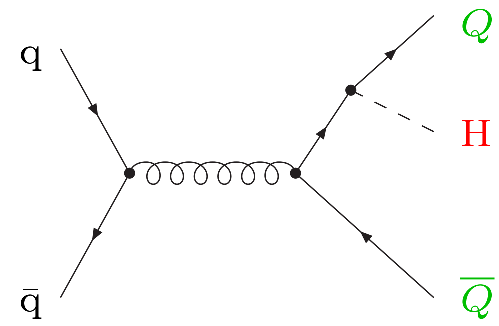
Higgs production with $\mathrm{t\bar{t}}$ or $\mathrm{b\bar{b}}$ pairs

Typical LO diagrams

. . . for gg fusion:



. . . for $\mathrm{q\bar{q}}$ annihilation:



$$Q\overline{Q} = \mathrm{t\bar{t}}, \mathrm{b\bar{b}}$$

Status of predictions:

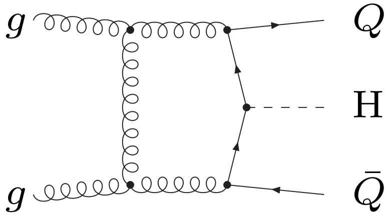
- LO Kunszt ’84; Dicus, Willenbrock ’89; Gunion ’91; Marciano, Paige ’91
- NLO for $\mathrm{t\bar{t}H}$ production Beenakker, S.D., Krämer, Plümper, Spira, Zerwas ’01,’02
  Dawson, Orr, Reina, Wackeroth ’02
  Wu, Ma, Hou, Zhang, Han, Jiang ’05

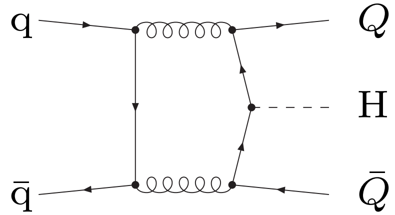
  for $\mathrm{b\bar{b}H}$ production S.D., Krämer, Spira ’03; Dawson, Jackson, Reina, Wackeroth ’05

Main complications in the predictions:

- Virtual NLO corrections:

  pentagon diagrams





etc.

$\hookrightarrow$ complicated singularity structure, potential numerical instabilities

$\Rightarrow$ techniques to avoid inverse Gram determinants in tensor integrals

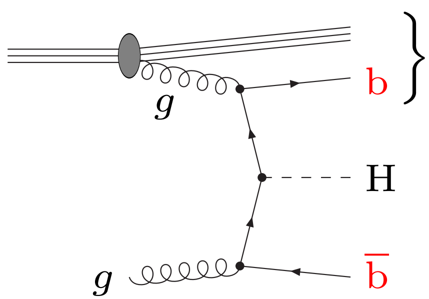
Denner, S.D. '02; etc.

- Real NLO corrections:

$\hookrightarrow$ involved matrix elements, multidimensional phase space,
complicated singularities $\Rightarrow$ dipole subtraction formalism

Catani, Seymour '96; Phaf, Weinzierl '01
Catani, S.D., Seymour, Trócsányi '02

- Peculiarity in $\mathrm{b\bar{b}H}$ production for untagged b's:



small b transverse momenta lead to large corrections

$\propto \alpha_\mathrm{s} \ln(m_\mathrm{b}/M_\mathrm{H})$

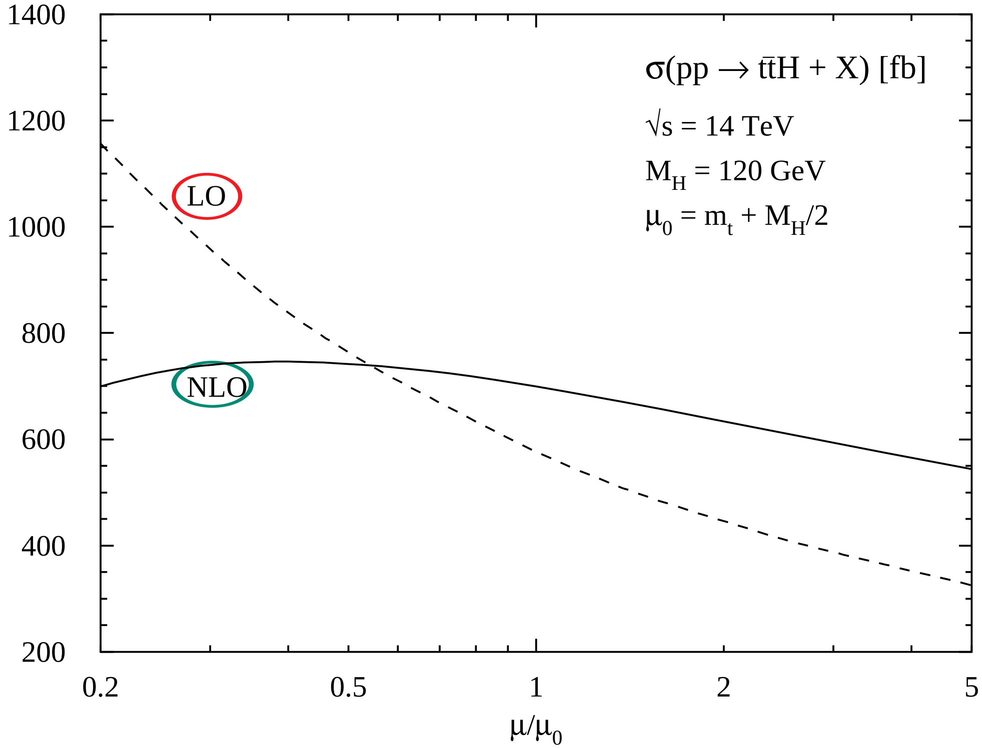
resummation of higher orders desirable !

$\hookrightarrow$ e.g. use b-quark distribution $\mathrm{b}(x, \mu_\mathrm{fact})$ with DGLAP evolution
that resums $[\alpha_\mathrm{s} \ln(m_\mathrm{b}/M_\mathrm{H})]^n$ terms

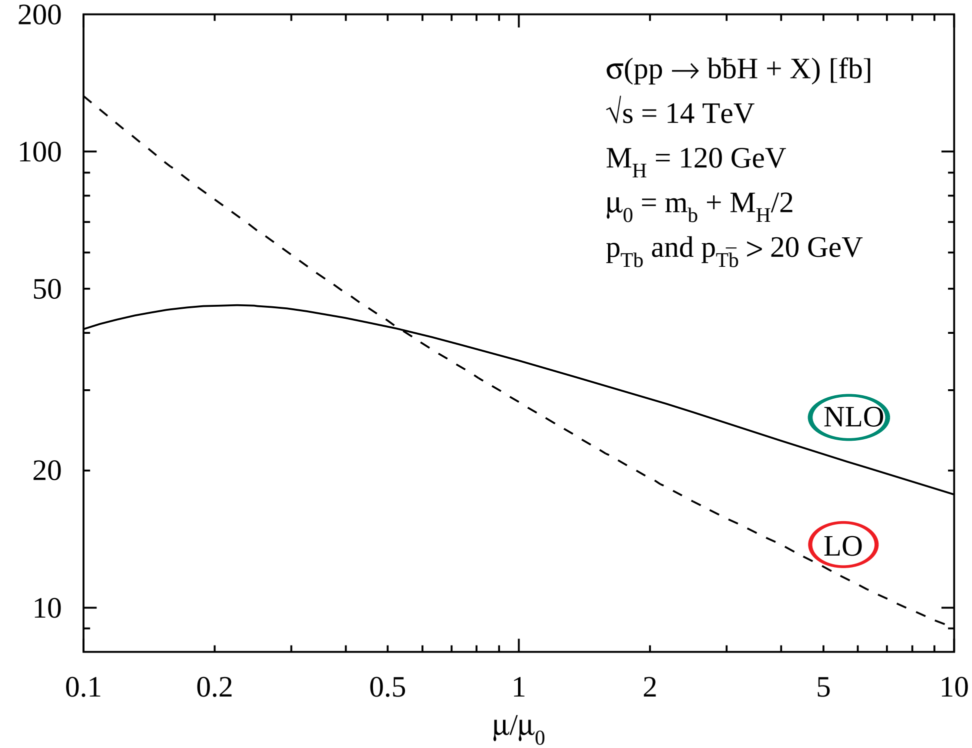
Barnett, Haber, Soper '88
Dicus, Willenbrock '89; etc.

Scale dependence of cross sections at the LHC

...for $\mathrm{t\bar{t}H}$ production: Beenakker et al. '03



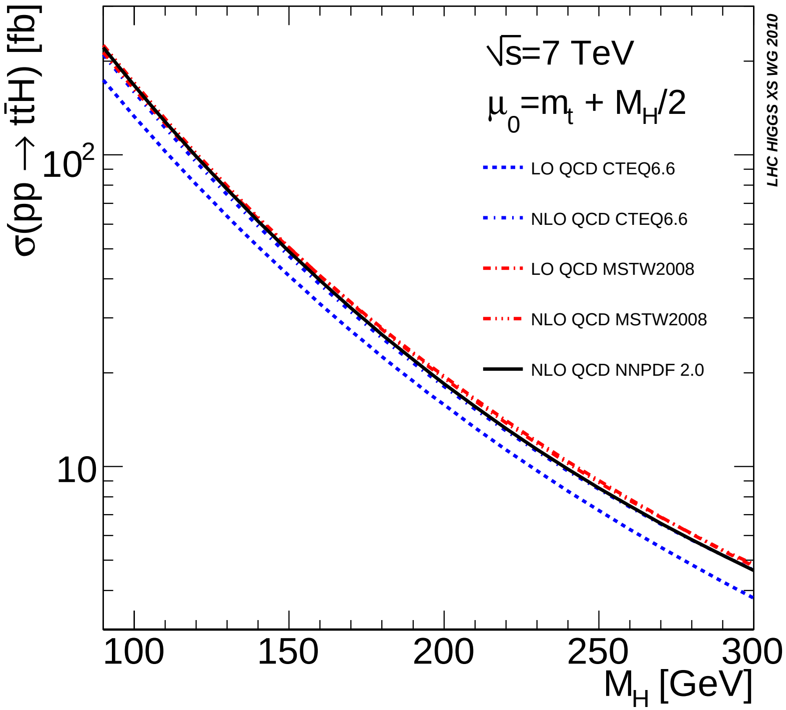
...for $\mathrm{b\bar{b}H}$ production: S.D., Krämer, Spira '03

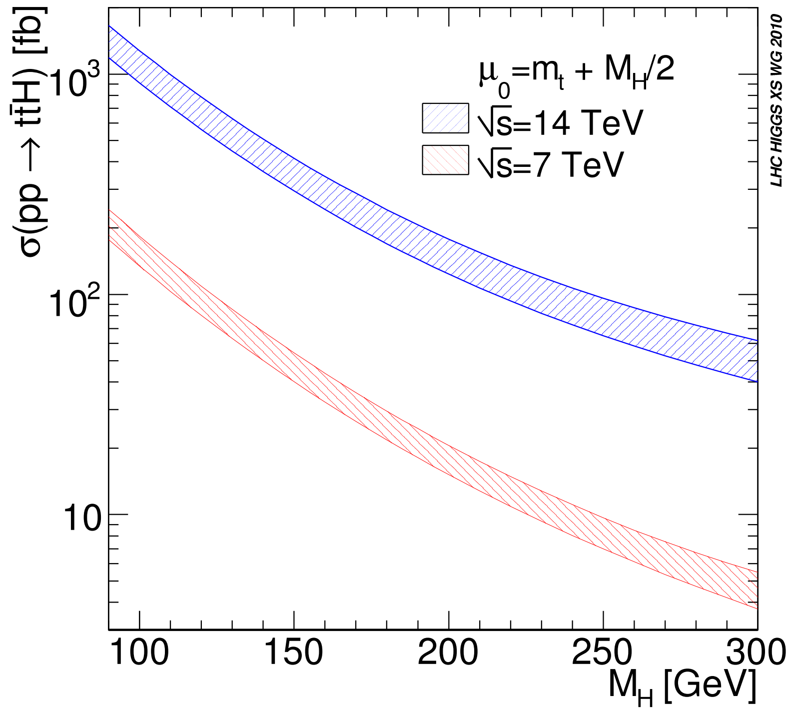


Drastic reduction of scale uncertainty in LO ($\sim 100\%$) $\rightarrow$ NLO (~ 10–20%)

Note: both both b's of $\mathrm{b\bar{b}H}$ tagged at $p_\mathrm{T} > 20\,\mathrm{GeV}$, otherwise scale dependence larger!

Total cross sections for ttH production at the LHC



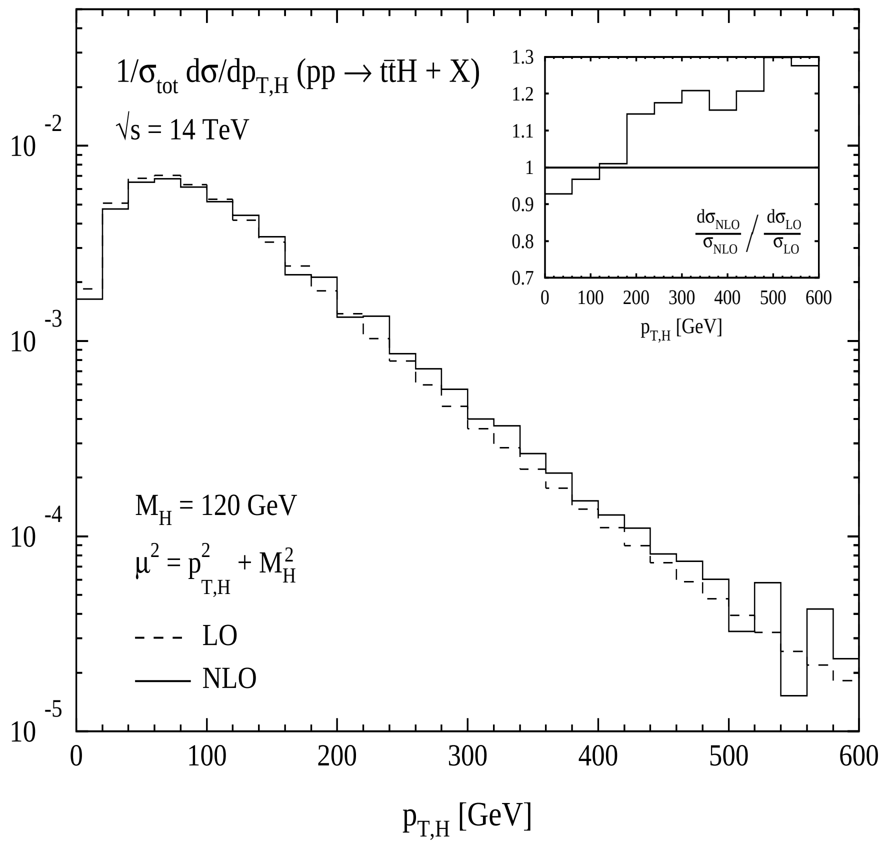


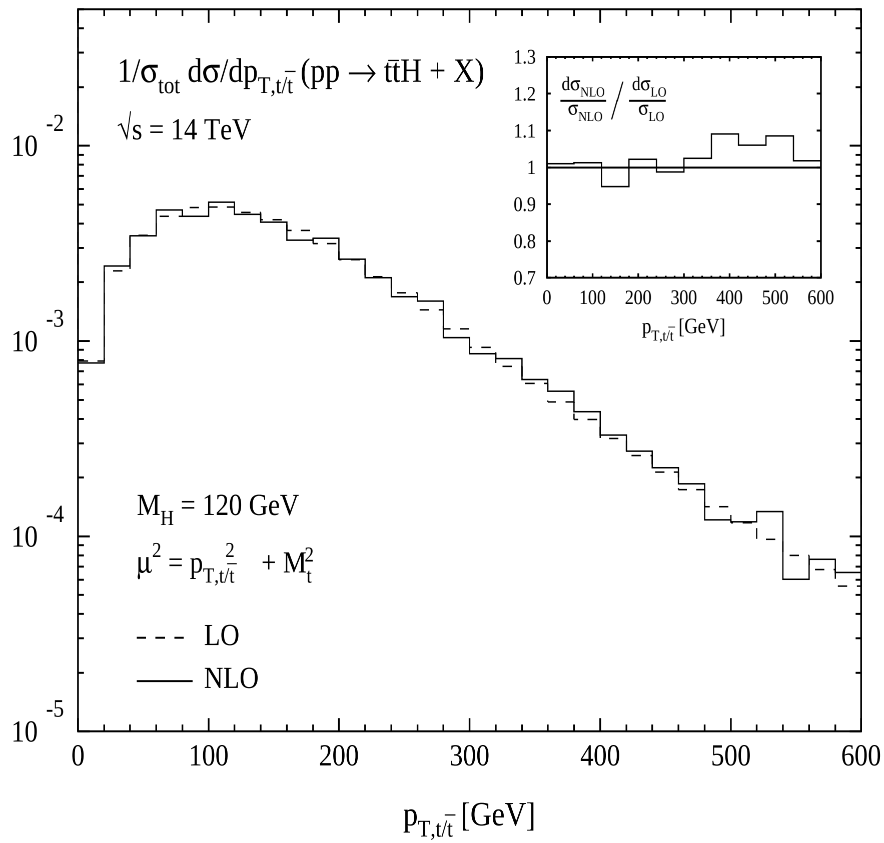
Some statements on uncertainties ($M_{\rm H} = 110{-}200\,{\rm GeV}$):

$E_{\rm CM}$	$7\,{\rm TeV}$	$14\,{\rm TeV}$
scale uncertainty ($\mu_0/2 < \mu < 2\mu_0$)	$+4\%, -9\%$	$+7\%, -10\%$
$\alpha_{\rm s} \oplus {\rm PDF}$ (a la PDF4LHC)	$\pm 9\%$	$\pm 9\%$

Transverse-momentum distributions for ttH production at the LHC

Beenakker et al. ’02





Note:

Dynamical scale significantly stabilizes NLO corrections, espacially for $t\bar{t}$!

Predictions for background processes

$\mathrm{pp} \to \mathrm{t\bar{t}b\bar{b}} + X$ **at NLO QCD**

At the LHC the background to some signals probably cannot be measured !

"Les Houches wishlist '05" of missing NLO predictions for 'multi-leg" background:

	background for
$\mathrm{pp} \to \mathrm{VV} + \mathrm{jet}$	$\mathrm{t\bar{t}H}$, new physics

WW+jet: S.D., Kallweit, Uwer '07,'09; Campbell, R.K.Ellis, Zanderighi '07; ZZ+jet: Binoth et al. '09
Wγ+jet: Campanario, Englert, Spannowsky, Zeppenfeld '09; WZ+jet: Campanario et al. + Kallweit '10

$\mathrm{pp} \to \mathrm{t\bar{t}b\bar{b}}$	$\mathrm{t\bar{t}H}$

Bredenstein, Denner, S.D., Pozzorini '08,'09; Bevilacqua, Czakon, Papadopoulos, Pittau, Worek '09

$\mathrm{pp} \to \mathrm{t\bar{t}} + 2\mathrm{jets}$	$\mathrm{t\bar{t}H}$

Bevilacqua, Czakon, Papadopoulos, Pittau, Worek '10

$\mathrm{pp} \to \mathrm{VVb\bar{b}}$	VBF $\to \mathrm{H} \to \mathrm{VV}$, $\mathrm{t\bar{t}H}$, new physics

Denner, S.D., Kallweit, Pozzorini '10; Bevilacqua, Czakon, van Hameren, Papadopoulos, Pittau, Worek '10

$\mathrm{pp} \to \mathrm{VV} + 2\mathrm{jets}$	VBF $\to \mathrm{H} \to \mathrm{VV}$

VBF: Jäger et al. '06,'09; Bozzi et al. '07; $\mathrm{W^+W^\pm}$jj(QCD): Melia, Melnikov, Rontsch, Zanderighi '10, '11

$\mathrm{pp} \to \mathrm{V} + 3\mathrm{jets}$	$\mathrm{t\bar{t}}$, new physics	$\mathrm{pp} \to \mathrm{W} + 4\mathrm{jets}$

W+3jets: R.K.Ellis, Melnikov, Zanderighi '09; Berger et al. '09
Z+3jets: Berger et al. '10

leading colour: Berger et al. '10

$\mathrm{pp} \to \mathrm{VVV}$	SUSY tri-lepton

Lazopoulos et al. '07; Binoth, Ossola, Papadopoulos, Pittau '08; Hankele, Zeppenfeld '08

$\mathrm{pp} \to \mathrm{b\bar{b}b\bar{b}}$	Higgs and new physics	(added 2007)

(Binoth,) Greiner, Guffanti, (Guillet,) Reiter, Reuter '09–'11

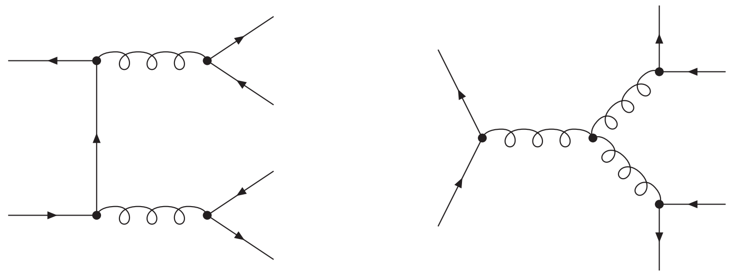
$\hookrightarrow$ Long-termed calculations for theorists ! (several 10^4 diagrams, many "(wo)men-decades")

The process $\mathrm{pp} \to \mathrm{t\bar{t}b\bar{b}}$ in NLO QCD

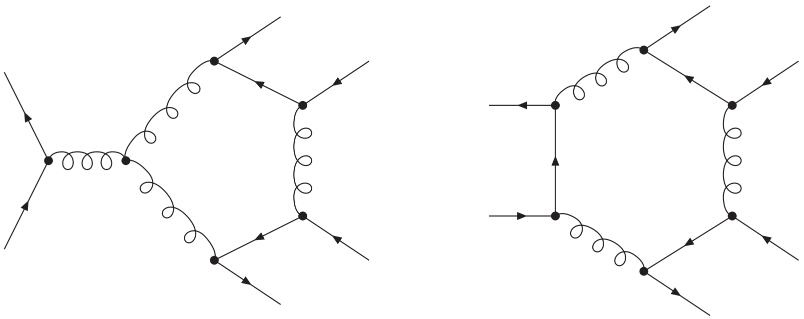
Bredenstein, Denner, S.D., Pozzorini ’08,’09;   Bevilacqua, Czakon, Papadopoulos, Pittau, Worek ’09

$q\bar{q} \to \mathrm{t\bar{t}b\bar{b}}$

LO: 7 tree graphs

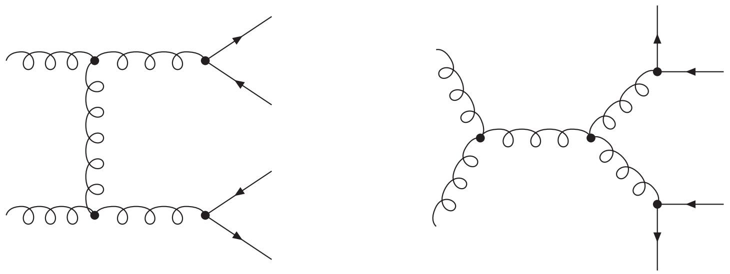


NLO: $\mathcal{O}(200)$ 1-loop diagrams
(24 pentagons, 8 hexagons)

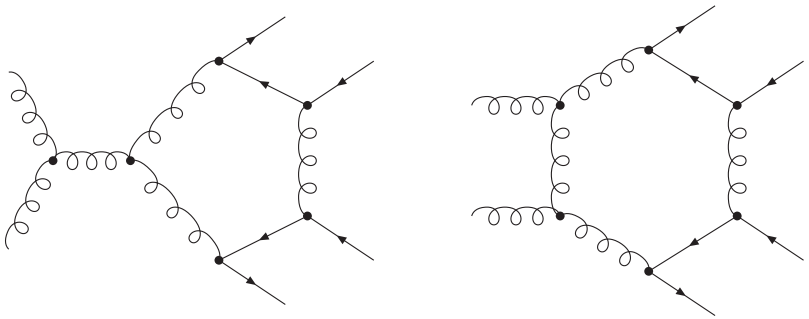


$\mathrm{gg} \to \mathrm{t\bar{t}b\bar{b}}$

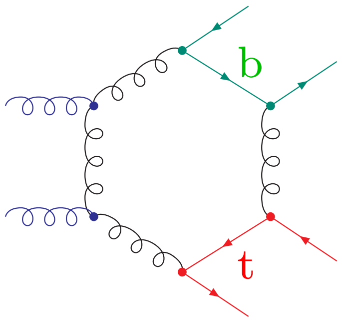
LO: 36 tree graphs



NLO: $\mathcal{O}(\gtrsim 1000)$ 1-loop diagrams
(> 100 pentagons, 40 hexagons)



$2 \to 4$ processes define present “NLO multi-leg frontier".



$$= \frac{g_\mathrm{s}^6}{2^4} f^{afc} f^{bfd} \mu^{2(4-D)} \int \frac{\mathrm{d}^D q}{(2\pi)^D} \varepsilon^{\alpha,a}(p_1)\, \varepsilon^{\beta,b}(p_2)$$

$$\times\, \overline{u}_{\mathrm{b},k}(k_3)\, (\lambda^e \lambda^c)_{kl}\, \gamma^\mu \frac{m_\mathrm{b} - \not{q}}{q^2 - m_\mathrm{b}^2} \gamma^\nu\, v_{\bar{\mathrm{b}},l}(k_4)$$

$$\times\, \overline{u}_{\mathrm{t},i}(k_1)\, (\lambda^d \lambda^e)_{ij}\, \gamma^\rho \frac{m_\mathrm{t} - \not{k}_2 - \not{k}_3 - \not{q}}{(q+k_2+k_3)^2 - m_\mathrm{t}^2} \gamma_\mu\, v_{\bar{\mathrm{t}},j}(k_2)$$

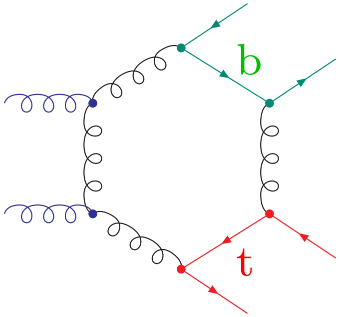
$$\times \frac{\Big[(q+2p_1-k_4)_\nu g_{\alpha\sigma} + (q-p_1-k_4)_\sigma g_{\nu\alpha} - (2q+p_1-2k_4)_\alpha g_{\nu\sigma}\Big]}{(q+k_3)^2\, (q+p_1+p_2-k_4)^2\, (q+p_1-k_4)^2\, (q-k_4)^2}$$

$$\times \Big[(2q+2p_1+p_2-2k_4)_\beta g_{\rho\sigma} - (q+p_1-p_2-k_4)_\rho g_{\beta\sigma} - (q+p_1+2p_2-k_4)_\sigma g_{\beta\rho}\Big]$$

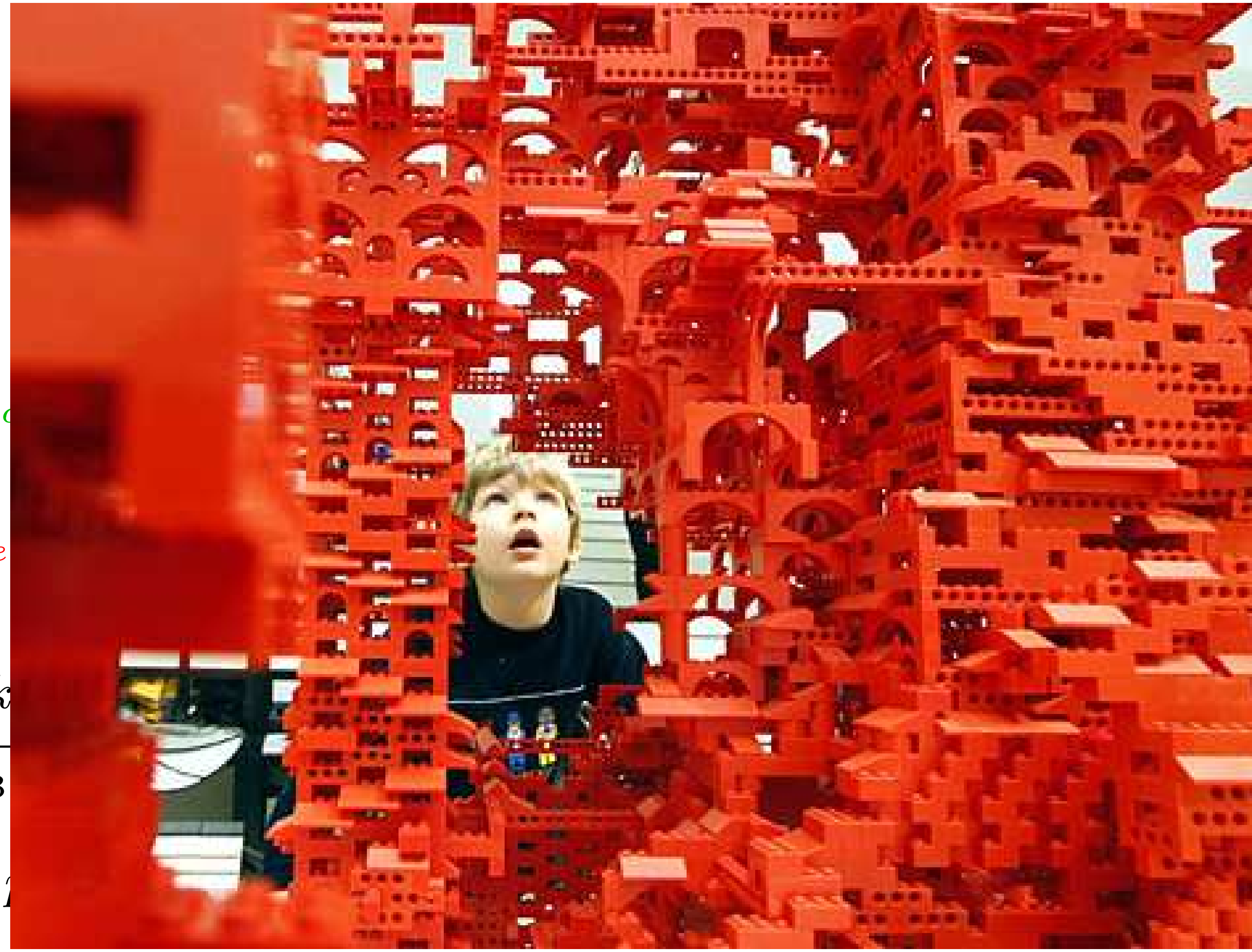
D-dim. integral over Minkowski momentum space contains

- various “soft” divergences
- various “collinear” divergences

$\hookrightarrow$ dimensional regularization turns divergences into poles $(D-4)^{-1}$ and $(D-4)^{-2}$



$=$



$\times\ \overline{u}_{\mathrm{b},k}(k_3)\,(\lambda^e\lambda$

$\times\ \overline{u}_{\mathrm{t},i}(k_1)\,(\lambda^d\lambda^e$

$\times\ \dfrac{\Big[(q+2p_1-k}{(q+k_3}$

$\times\ \Big[(2q+2p_1+ \quad \ldots \quad {}_4)_\sigma g_{\beta\rho}\Big]$

D-dim. integral over Minkowski momentum space contains

- various “soft” divergences
- various “collinear” divergences

$\hookrightarrow$ dimensional regularization turns divergences into poles $(D-4)^{-1}$ and $(D-4)^{-2}$

Main difficulties in the loop calculation:

- Algebraic complexity

  Generation of graphs / amplitudes via computer algebra (MATHEMATICA)

  $\hookrightarrow$ computer-algebraic reduction to standard form

  $\hookrightarrow$ $\sim$ 1.4 Mio automatically generated lines of code

- Analytic structure

  Difficult loop integrals with UV and IR divergences

  $\hookrightarrow$ regularization in $D \neq 4$ space-time dimensions

  $\hookrightarrow$ elimination of UV divergences via renormalization

- Numerical stability

  Strong cancellation between contributions to loop integrals

  $\hookrightarrow$ dedicated methods for dangerous phase-space regions

- Efficient numerical evaluation

  Goal: fast, numerically stable evaluation in $\lesssim 1\mathrm{sec/event}$

  $\hookrightarrow$ appropriate algorithms, optimizations, cache systems, etc.

  our result: $\mathcal{M}_{1-\mathrm{loop}}^{q\bar{q}/\mathrm{gg}\to\mathrm{t\bar{t}b\bar{b}}}$ in $\mathcal{O}(0.2\mathrm{sec/event})$

Our Feynman-diagrammatic approach for virtual 1-loop corrections

$$\mathcal{M}_{1-\mathrm{loop}} = \sum_{\mathrm{(sub)diagrams}\ \Gamma} \mathcal{M}_\Gamma$$ generated with FeynArts (Küblbeck et al. '90; Hahn '01)

$$\mathcal{M}_\Gamma = \sum_n \underbrace{C^{(\Gamma)}}_{\text{colour factor}} \underbrace{F_n^{(\Gamma)}}_{\uparrow} \underbrace{\hat{\mathcal{M}}_n}_{\text{spin structures like } [\bar{u}_\mathrm{t}(k_\mathrm{t})\not{\varepsilon}_{\mathrm{g}_1}(k_{\mathrm{g}_1})v_{\bar{\mathrm{t}}}(k_{\bar{\mathrm{t}}})](\varepsilon_{\mathrm{g}_2}(k_\mathrm{g})\cdot k_\mathrm{t})\dots}$$

invariant functions containing

1-loop tensor integrals $T^{\mu\nu\rho\dots}$

$$T^{\mu\nu\rho\dots} = (p_k^\mu p_l^\nu p_m^\rho \dots)T_{kl\dots} + (g^{\mu\nu} p_m^\rho \dots)T_{00m\dots} + \dots$$

$T_{kl\dots}$ = linear combination of scalar 1-loop integrals A_0, B_0, C_0, D_0

– recursively calculable à la Passarino/Veltman '79 for regular points

– specially designed methods for rescuing cases with small Gram dets. Denner, S.D. '05

– 5-/6-point integrals reduced to 4-point integrals Denner, S.D. '02,'05

Features:

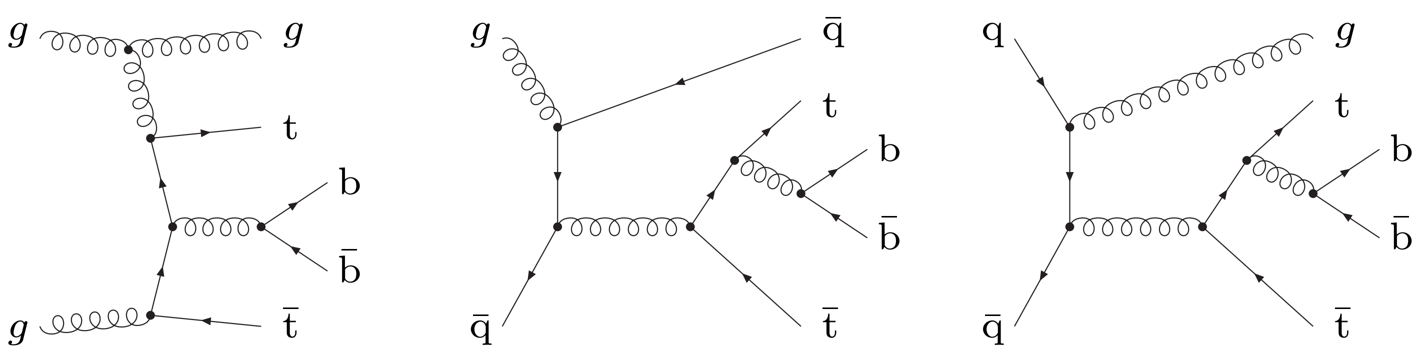
– advantage: get all colour/spin channels in one stroke

$\hookrightarrow$ speed: $\mathcal{M}_{1-\mathrm{loop}}^{q\bar{q}/\mathrm{gg}\to\mathrm{t\bar{t}b\bar{b}}}$ in $\mathcal{O}(0.2\mathrm{sec/event})$ very fast !

– lengthy algebra $\to$ automation (Mathematica)

– two independent calculations, one using features of FormCalc (Hahn)

Corrections due to real radiation



etc.

Salient features:

- fast evaluation of amplitudes $\longrightarrow$ spinor methods / MADGRAPH Stelzer, Long
- multi-channel Monte Carlo integration over phase space
- soft and collinear divergences
  $\hookrightarrow$ dipole subtraction formalism

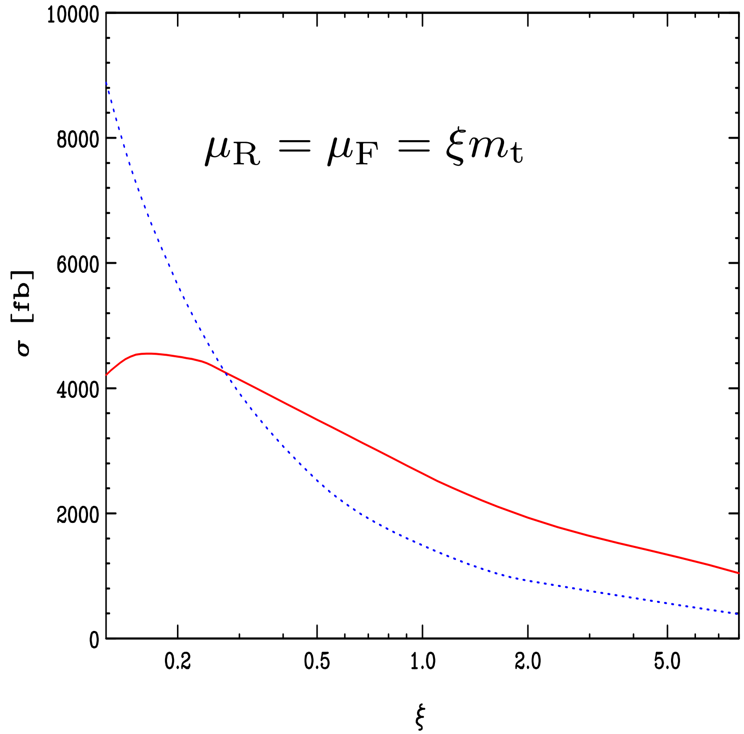
  Catani, Seymour '96; S.D. '99
  Phaf, Weinzierl '01
  Catani, S.D., Seymour, Trócsányi '02

$$\sigma^{\rm NLO} = \underbrace{\int_{m+1}\left[{\rm d}\sigma^{\rm real} - {\rm d}\sigma^{\rm sub}\right]}_{\text{finite}} + \underbrace{\int_{m}\left[{\rm d}\sigma^{\rm virtual} + {\rm d}\bar{\sigma}_1^{\rm sub}\right]}_{\text{finite}} + \int_0^1 {\rm d}x \underbrace{\int_{m}\left[{\rm d}\sigma^{\rm fact}(x) + \left({\rm d}\bar{\sigma}^{\rm sub}(x)\right)_+\right]}_{\text{finite}}$$

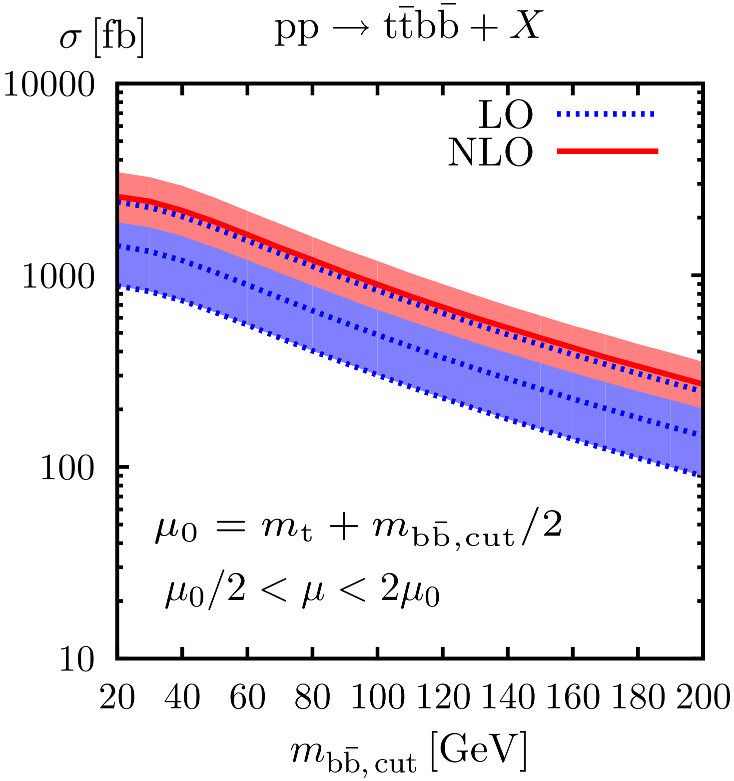
- two alternative IR regularizations: dim. reg. / mass reg. (small $m_{\rm q}, m_{\rm b}$)

NLO cross section for constant scale choice

Bevilacqua, Czakon, Papadopoulos, Pittau, Worek '09



Bredenstein, Denner, S.D., Pozzorini '09



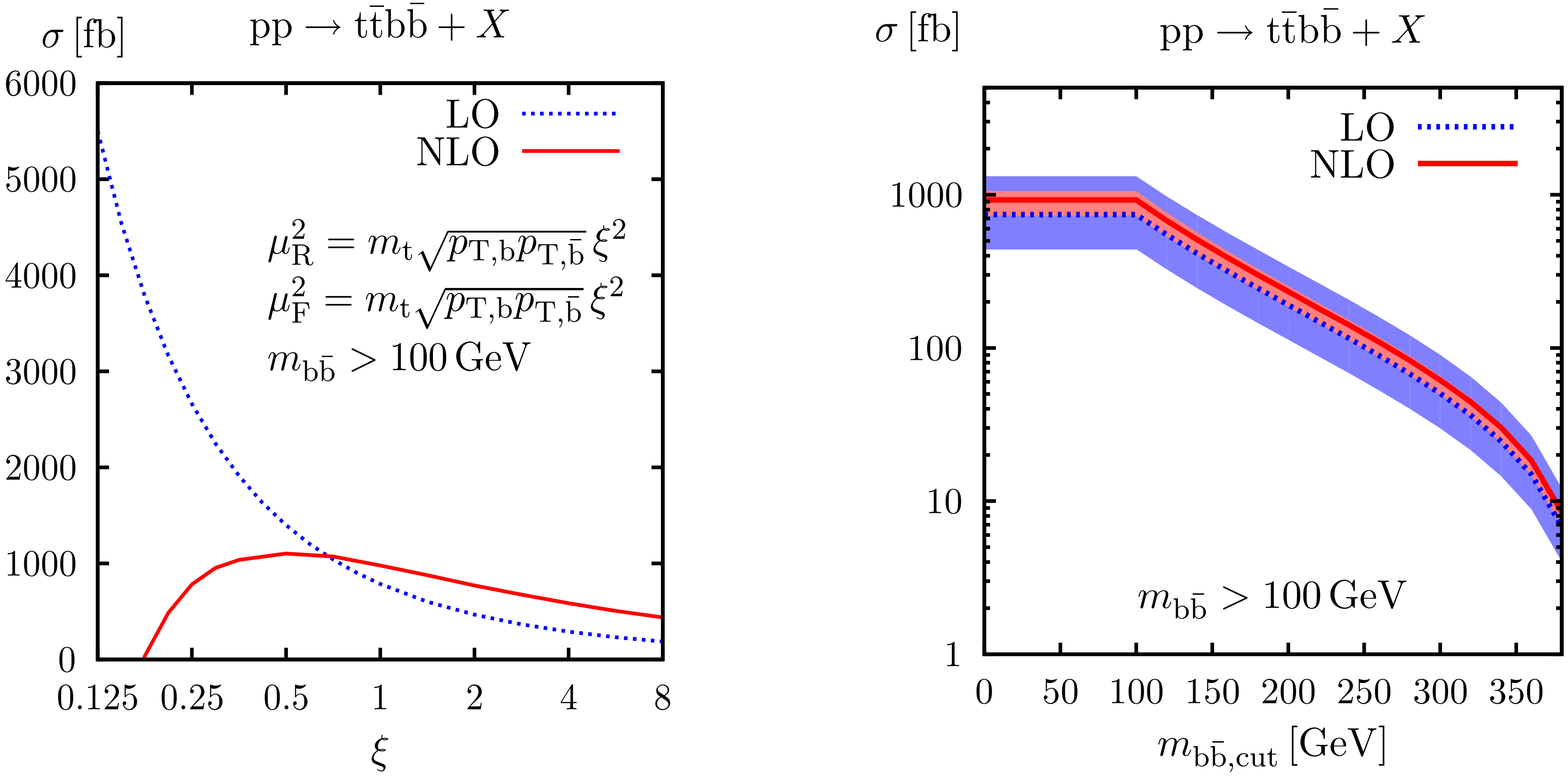
Main results:

- results of the two groups agree at the 0.1% level
- correction very large at central scale $\mu_{R/F} = m_t$: $K = 1.77$
- NLO scale dependence still large: $\sim 33\%$ for $\mu_0/2 < \mu_{R/F} < 2\mu_0$ ($\sim 70\%$ at LO)

$\hookrightarrow$ further theoretical and/or phenomenological tricks necessary to stabilize analysis

NLO cross section for dynamical scale choice

Bredenstein, Denner, S.D., Pozzorini '10



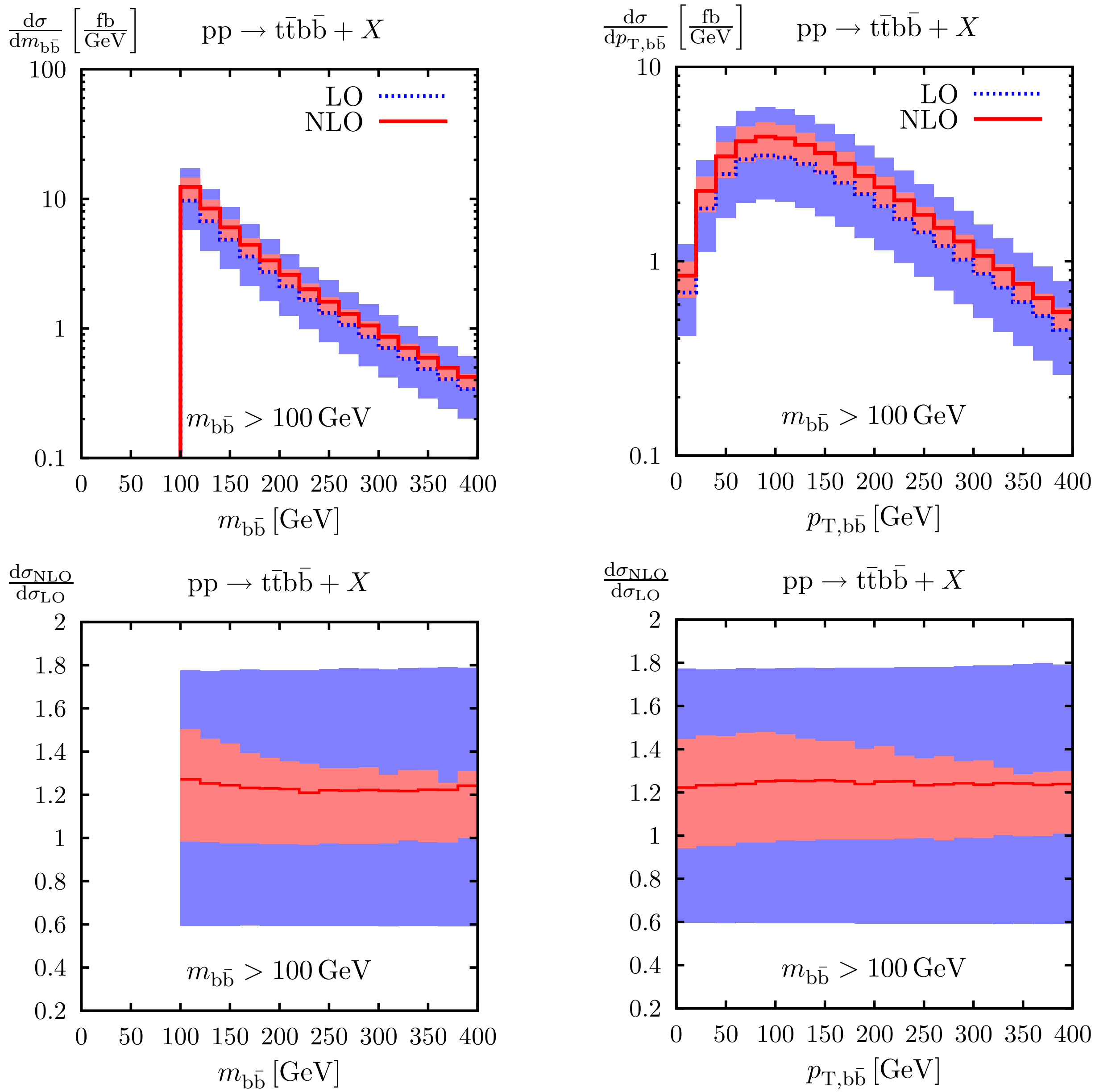
Dynamical scale: $\mu_0^2 = m_t\sqrt{p_{T,b}p_{T,\bar{b}}}$

- smaller correction at central scale $\mu_{R/F} = \mu_0$: $K = 1.24$ $(m_{b\bar{b}} > 100\,\mathrm{GeV})$
- NLO scale dependence reduced: $\sim 21\%$ for $\mu_0/2 < \mu_{R/F} < 2\mu_0$ ($\sim 78\%$ at LO)

Distributions for $\mathrm{pp} \to \mathrm{t\bar{t}b\bar{b}} + X$ at NLO

Invariant mass and p_T of the $\mathrm{b\bar{b}}$ pair:

Bredenstein, Denner,
S.D., Pozzorini ’10

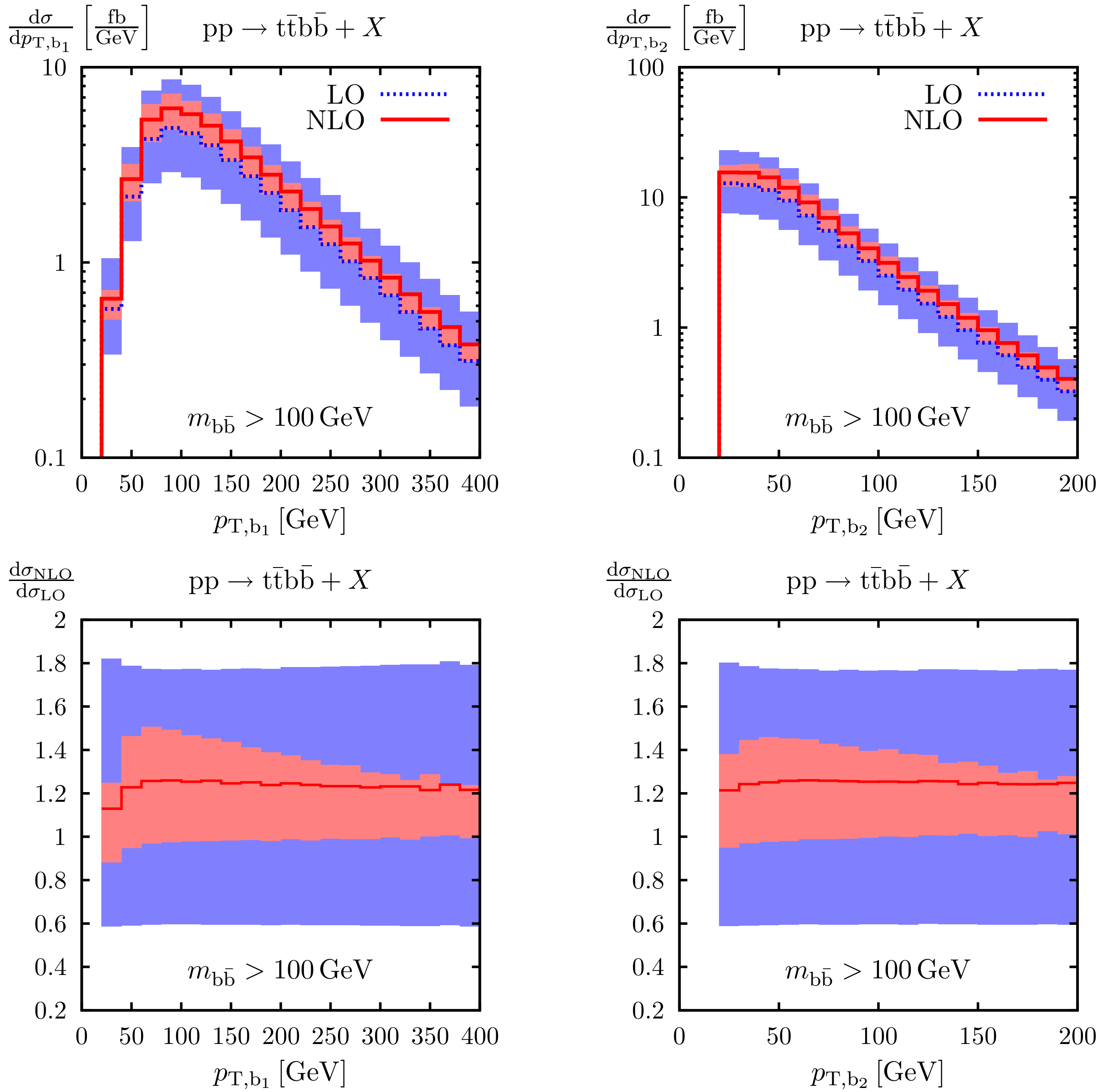


Corrections show little phase-space variations

Distributions for $\mathrm{pp} \to \mathrm{t\bar{t}b\bar{b}} + X$ at NLO

p_T of the b quarks ($p_{\mathrm{T,b_1}} > p_{\mathrm{T,b_2}}$):

Bredenstein, Denner, S.D., Pozzorini '10



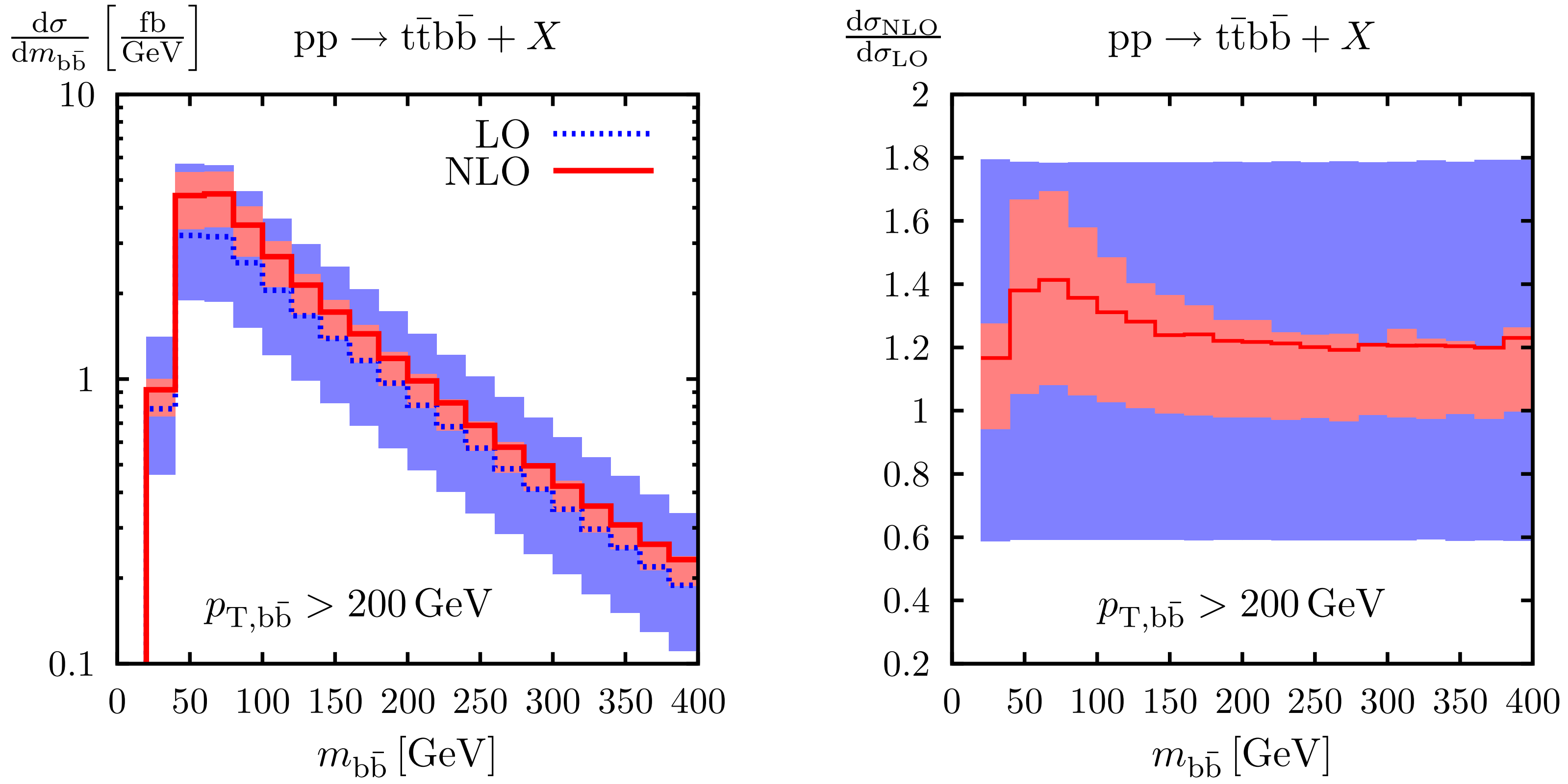
Corrections show little phase-space variations

Simulating $\mathrm{H} \to \mathrm{b\bar{b}}$ with high p_T

$\hookrightarrow$ impose cuts $p_{\mathrm{T,b\bar{b}}} > 200\,\mathrm{GeV}$

Invariant mass of the $\mathrm{b\bar{b}}$ pair:

Bredenstein, Denner, S.D., Pozzorini ’10



Note: corrections induce distortion in signal region !

Conclusions

Conclusions

$\mathrm{pp} \to \mathrm{t\bar{t}H}(\to \mathrm{b\bar{b}})$ at the LHC

- important for Higgs Yukawa coupling determination
- experimentally very challenging:
  signal swamped by background in experimental studies
  $\hookrightarrow$ more sophisticated tricks in analysis needed (fat jets at high p_{T}?)
  NLO predictions for background in data-driven analysis
- $\mathrm{pp} \to \mathrm{t\bar{t}b\bar{b}}$ = most important background process

$\mathrm{pp} \to \mathrm{t\bar{t}b\bar{b}}$ at NLO QCD

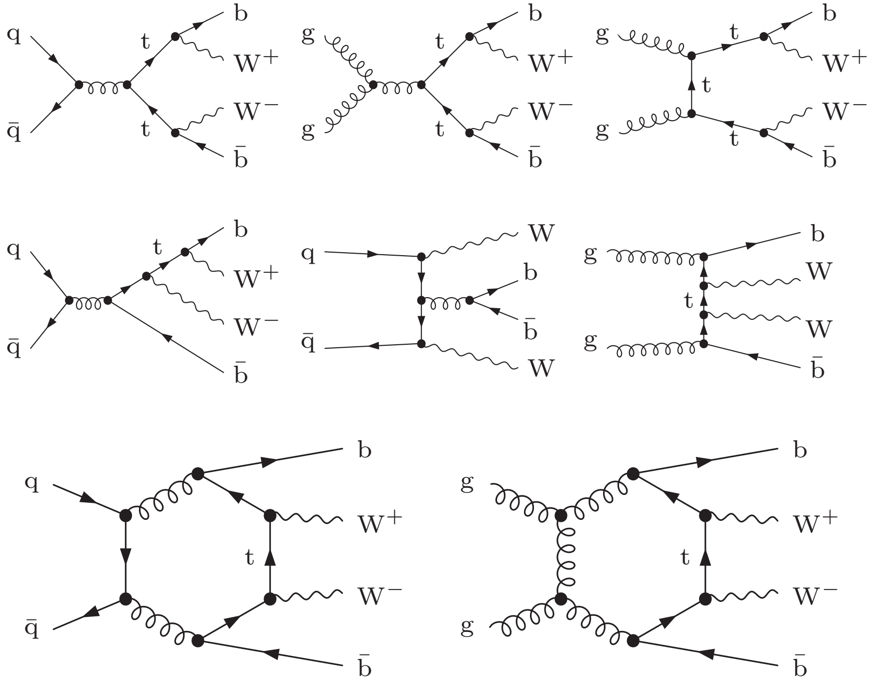
- calculated by our group with Feynman-diagrammatic technique
  $\hookrightarrow$ fast and numerically stable evaluation
- dynamical scale choice needed to receive good perturbative stability
  $\hookrightarrow$ reduced scale uncertainty / relatively flat K factors in distributions
- background in LO-based experimental studies even underestimated
- NLO cross section confirmed in 2nd calculation at 0.1% level

New experimental analysis of $\mathrm{pp} \to \mathrm{t\bar{t}H}(\to \mathrm{b\bar{b}})$ highly desirable

Outlook to WWbb production

From ttbb to WWbb at NLO QCD:

Denner, S.D., Kallweit, Pozzorini ’10
Bevilacqua, Czakon, van Hameren, Papadopoulos, Worek ’10

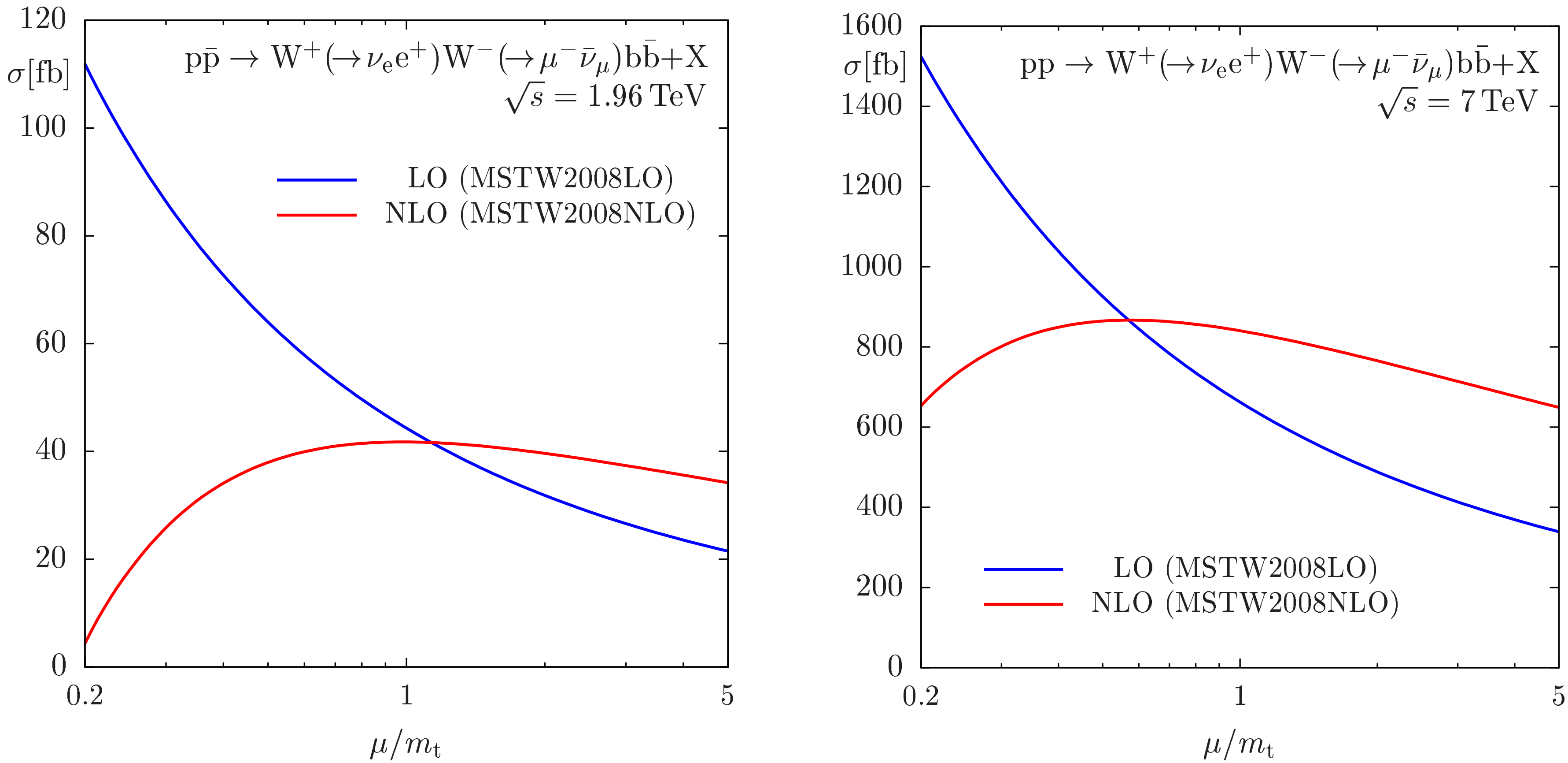


Feautures (of our calculation):

- $\sim 800(300)$ 1-loop diagrams in gg $(\mathrm{q\bar{q}})$
  (86 pentagons, 21 hexagons in gg)
- our loop machinery still fast and stable
- higher algebraic complexity:
  hexagon tensors up to rank 5
  $\hookrightarrow$ $4{-}5$ Mio Fortran lines for virtual corrections
- top-quark resonances
  $\hookrightarrow$ gauge-invariant treatment via “complex-mass scheme”
  Denner, S.D., Roth, Wieders ’05
- leptonic W-boson decays included via improved narrow-width approximation
  $\hookrightarrow$ W spin correlations respected
- work in progress:
  - more phenomenological studies
  - tuned comparison with results of Bevilacqua et al.

Results on integrated cross sections

Denner, S.D., Kallweit, Pozzorini '10

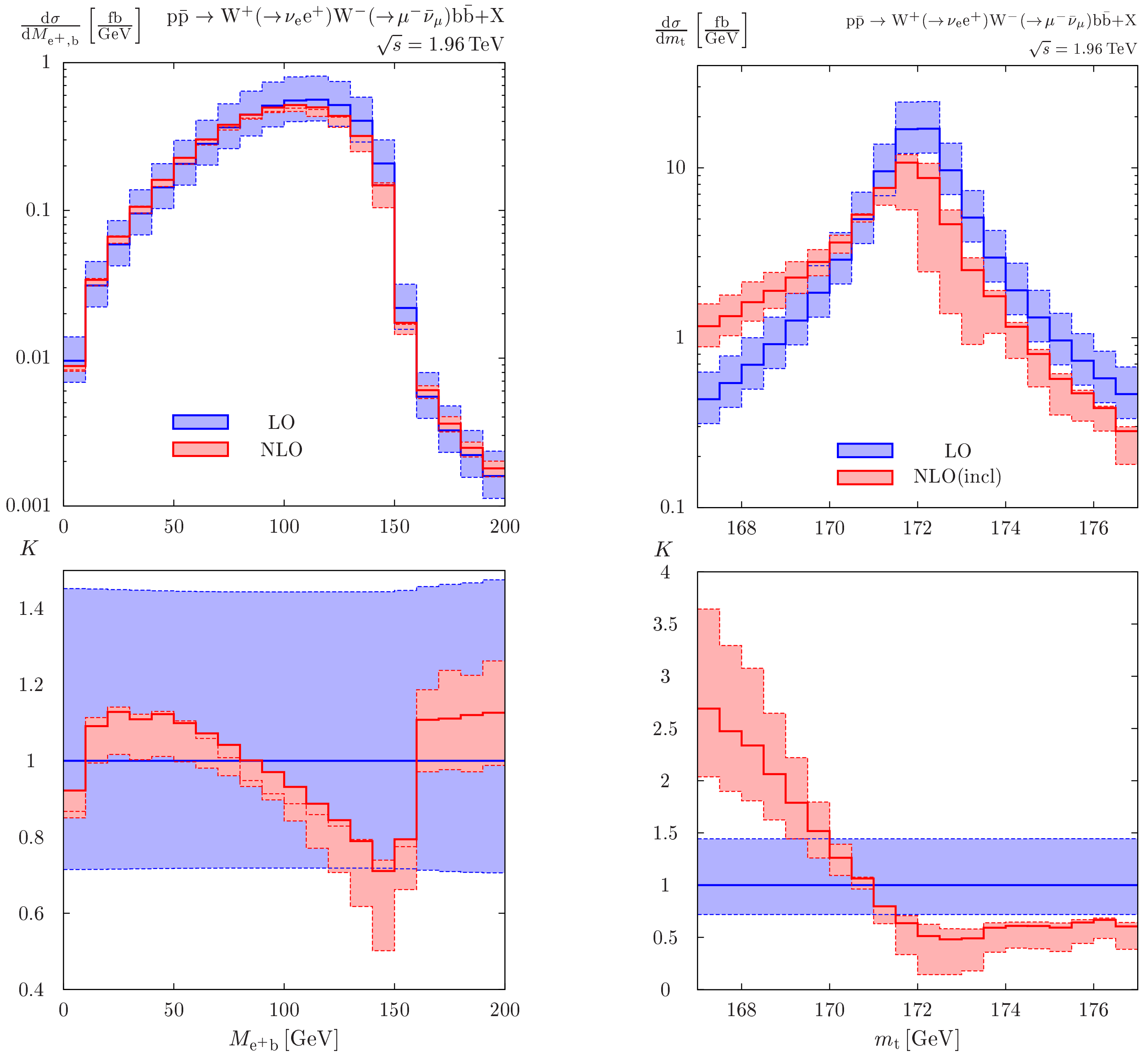


Size off-shell effects:

- $\mathcal{O}(1\%)$ for integrated quantities (quantified by comparing with limit $\Gamma_t \to 0$)
- larger for distributions, especially near kinematical edges of on-shell tops

Some differential cross sections at the Tevatron

Denner, S.D., Kallweit, Pozzorini ’10

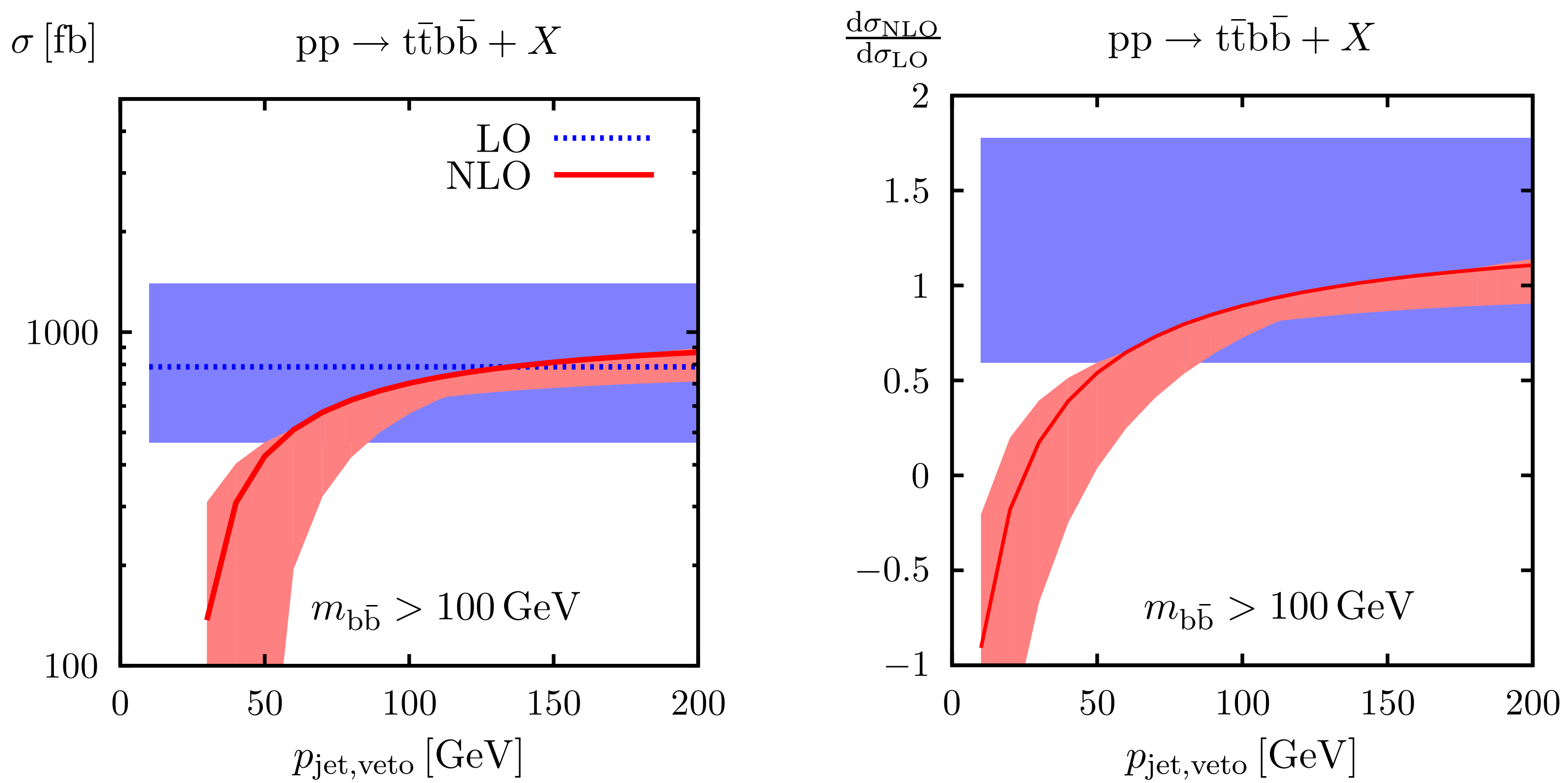


Backup slides

Reduction of large corrections via jet veto ?

$\hookrightarrow$ veto against jets with $p_{\mathrm{T,jet}} > p_{\mathrm{jet,veto}}$

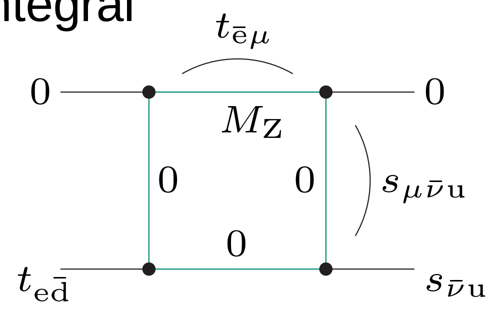
Bredenstein, Denner, S.D., Pozzorini '10



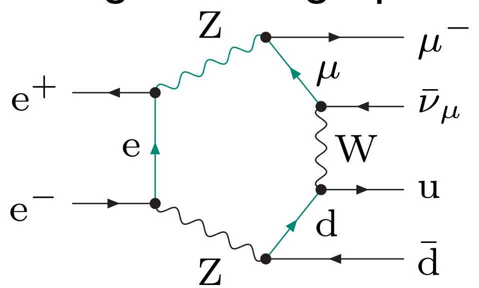
- trade-off:
  - $p_{\mathrm{jet,veto}}$ too large $\rightarrow$ no reduction of σ
  - $p_{\mathrm{jet,veto}}$ too small $\rightarrow$ perturbative instability
- compromise: $p_{\mathrm{jet,veto}} \sim 100\,\mathrm{GeV}$ $\rightarrow$ $K \sim 0.9$, scale uncertainty $\sim 20\%$

A typical example with small Gram determinant:

Box integral

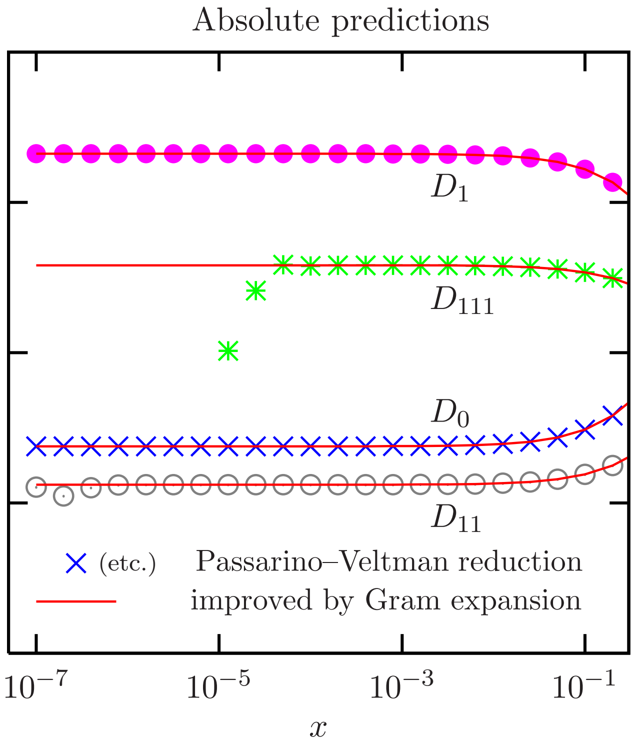


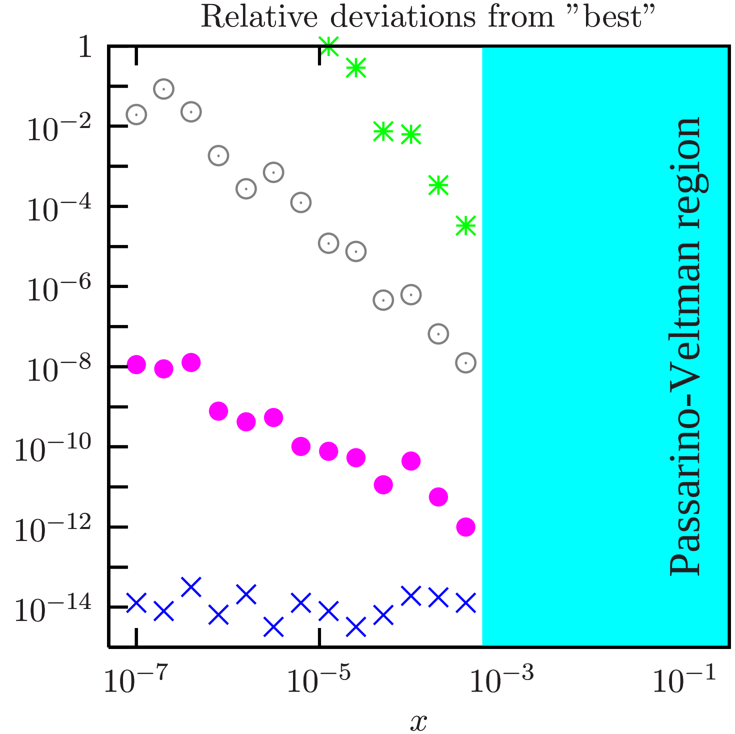
appears, e.g., in subgraph of diagram



Gram det.: $\det(\text{Gram}) \to 0$ if $t_{e\bar{d}} \to t_{crit} \equiv \dfrac{s_{\mu\bar{\nu}u}(s_{\mu\bar{\nu}u} - s_{\bar{\nu}u} + t_{\bar{e}\mu})}{s_{\mu\bar{\nu}u} - s_{\bar{\nu}u}}$

Numerical comparison: maximal tensor rank $= 6$ (similar to $ee \to 4f$ application)





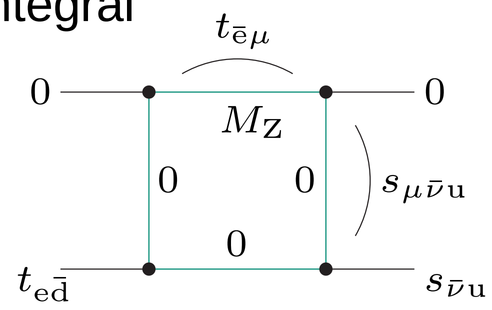
$x \equiv \dfrac{t_{e\bar{d}}}{t_{crit}} - 1$

$$
\begin{aligned}
s_{\mu\bar{\nu}u} &= +2\times 10^4\ \text{GeV}^2 \\
s_{\bar{\nu}u} &= +1\times 10^4\ \text{GeV}^2 \\
t_{\bar{e}\mu} &= -4\times 10^4\ \text{GeV}^2 \\
t_{crit} &= -6\times 10^4\ \text{GeV}^2
\end{aligned}
$$

PV reduction breaks down,
but Gram exp. stable
for $\det(\text{Gram}) \to 0$!

A typical example with small Gram determinant:

Box integral



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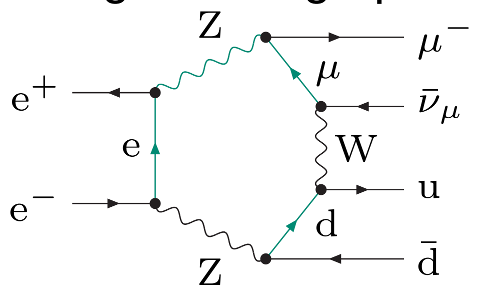
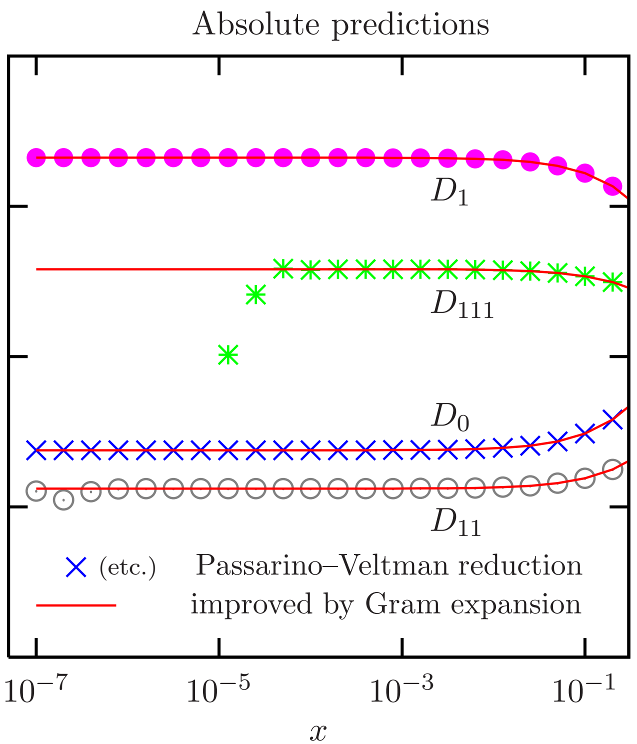
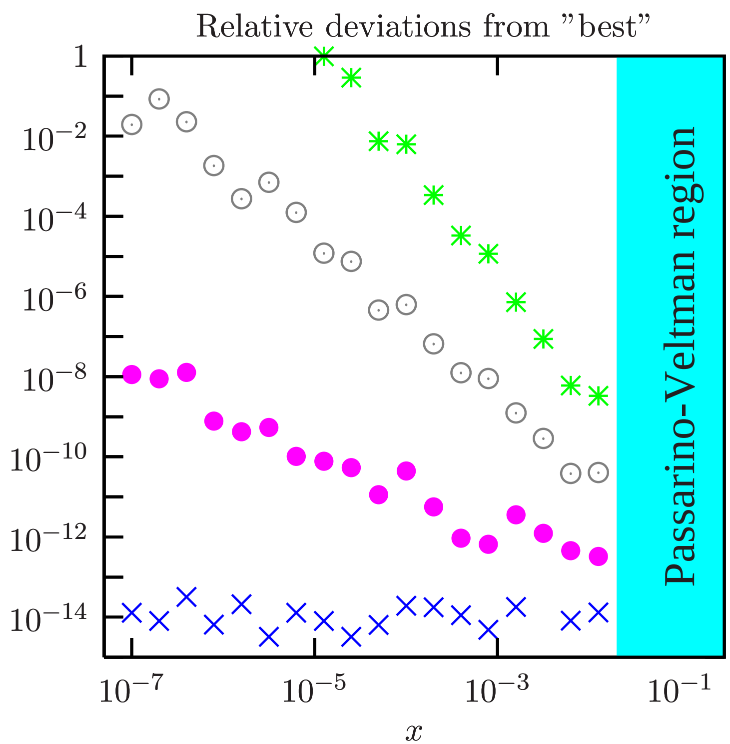


Gram det.: $\det(\text{Gram}) \to 0$ if $t_{e\bar{d}} \to t_{\text{crit}} \equiv \dfrac{s_{\mu\bar{\nu}u}(s_{\mu\bar{\nu}u} - s_{\bar{\nu}u} + t_{\bar{e}\mu})}{s_{\mu\bar{\nu}u} - s_{\bar{\nu}u}}$

Numerical comparison: maximal tensor rank $= 12$





$x \equiv \dfrac{t_{e\bar{d}}}{t_{\text{crit}}} - 1$

$$
\begin{aligned}
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s_{\bar{\nu}u} &= +1\times 10^4\ \text{GeV}^2\\
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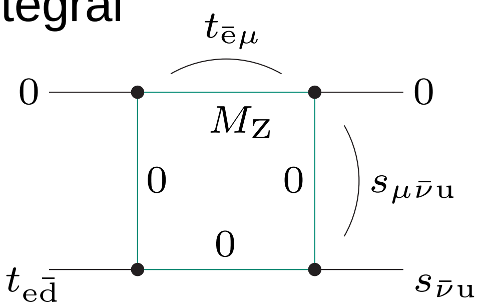
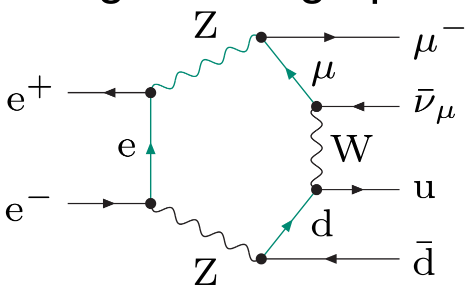
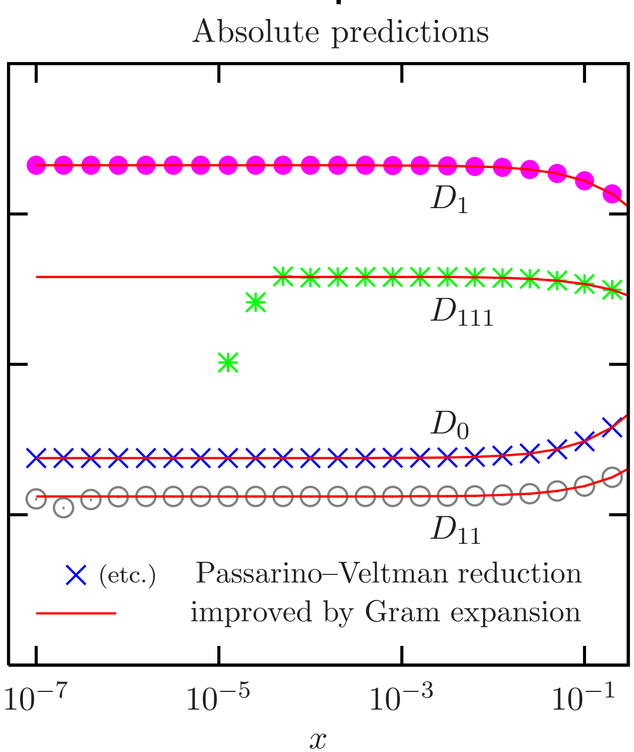


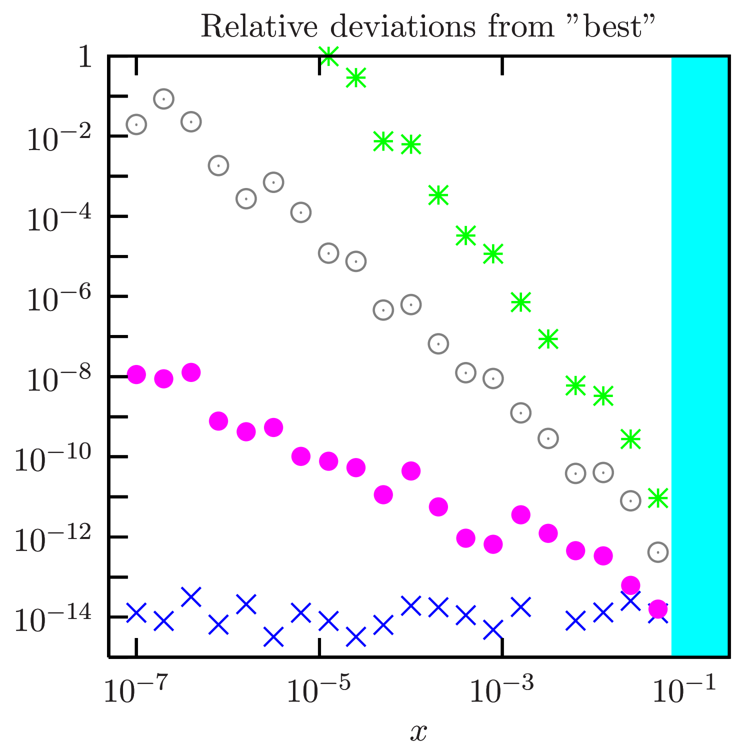
appears, e.g., in subgraph of diagram



Gram det.: $\det(\mathrm{Gram}) \to 0$ if $t_{e\bar{d}} \to t_{\mathrm{crit}} \equiv \dfrac{s_{\mu\bar{\nu}u}(s_{\mu\bar{\nu}u} - s_{\bar{\nu}u} + t_{\bar{e}\mu})}{s_{\mu\bar{\nu}u} - s_{\bar{\nu}u}}$

Numerical comparison: maximal tensor rank $= 25$





$x \equiv \dfrac{t_{e\bar{d}}}{t_{\mathrm{crit}}} - 1$

$s_{\mu\bar{\nu}u} = +2\times10^4\ \mathrm{GeV}^2$

$s_{\bar{\nu}u} = +1\times10^4\ \mathrm{GeV}^2$

$t_{\bar{e}\mu} = -4\times10^4\ \mathrm{GeV}^2$

$t_{\mathrm{crit}} = -6\times10^4\ \mathrm{GeV}^2$

PV reduction breaks down,
but Gram exp. stable
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