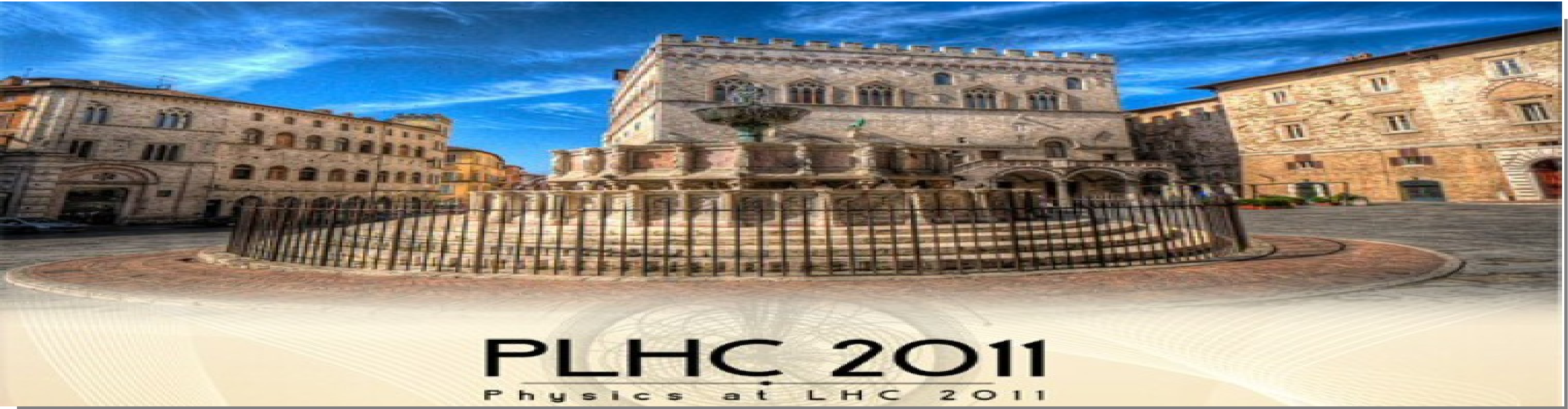


Status of Higher Order Effects in QCD and Electroweak Cross Sections at the LHC

Radja Boughezal

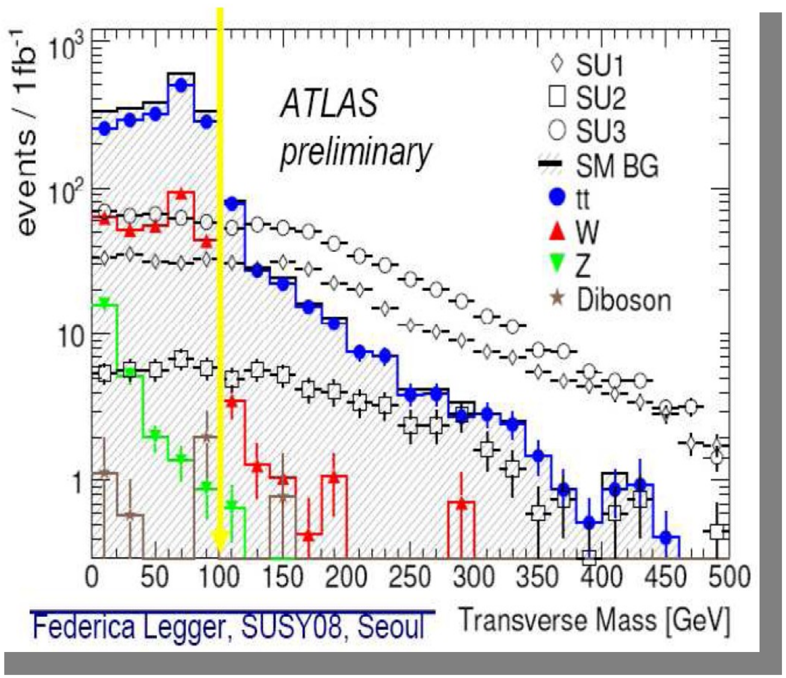
Argonne National Laboratory

Outline

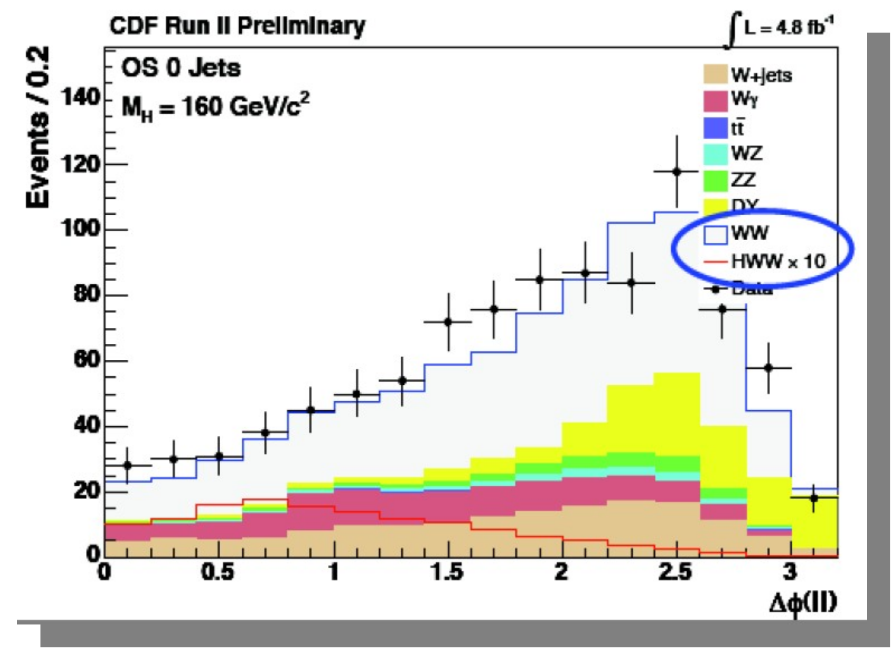
- Motivation: why we care about QCD at higher orders
- Progress in multileg NLO calculations
- QCD at NNLO and beyond: strong coupling constant and the Higgs cross section
- Conclusions

Why Do We Care about QCD?

- Not all discoveries are easy at LHC, don't always get a resonance peak or sharp kinematic structure

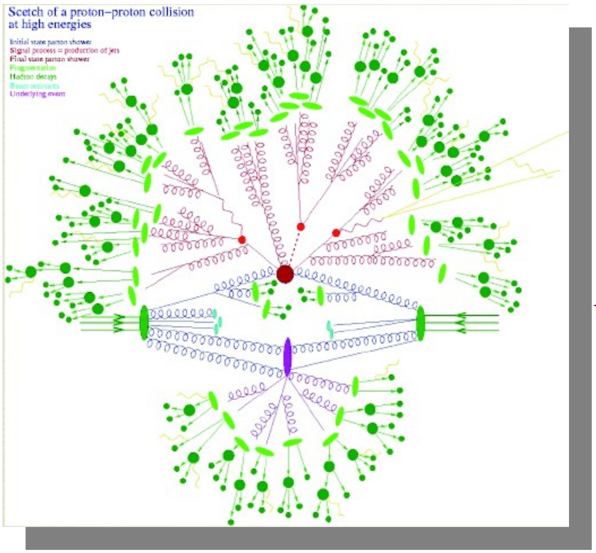


Do we understand the QCD shape Prediction for W/Z + jets?



Can we accurately predict the di-boson production rate?

Collisions at Hadron Colliders



How do we make a prediction for such an event?

Multiple physics effects living at widely varying scales

- Factorization: separate hard and soft scales

$$\sigma_{h_1 h_2 \to X} = \int dx_1 dx_2 \underbrace{f_{h_1/i}(x_1; \overbrace{\mu_F^2}^{\text{factorization scale}}) f_{h_1/j}(x_2; \mu_F^2)}_{PDFs} \underbrace{\sigma_{ij \to X}(x_1, x_2, \mu_F^2, \{q_k\})}_{\text{partonic cross section}} + \underbrace{\mathcal{O}\left(\frac{\Lambda_{QCD}}{Q}\right)^n}_{\text{power corrections}}$$

Non-perturbative but *universal*; measure in deep-inelastic scattering, fixed-target, apply to Tevatron, LHC

Process dependent but calculable in pQCD

Small for sufficiently inclusive observables

- Focus of this talk is a precise understanding of $\sigma_{ij \to X}(x_1, x_2, \mu_F^2, q_k)$

Computing the Cross Section

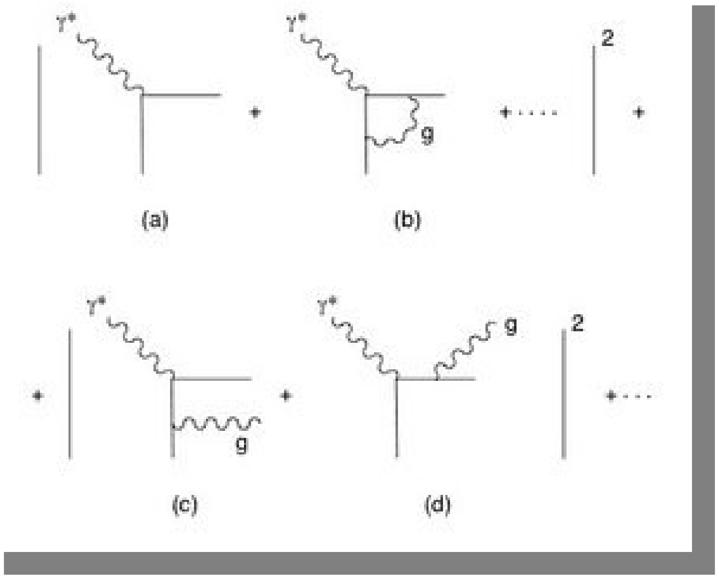
$$\sigma = \overbrace{\sigma_0}^{LO} + \overbrace{\frac{\alpha_s}{\pi}\sigma_1}^{NLO} + \overbrace{\left(\frac{\alpha_s}{\pi}\right)^2}^{NNLO}\sigma_2 + \ldots$$

Known for all processes of interest

need to understand higher orders

- Higher order corrections require real and virtual contributions in order to cancel infrared singularities

NLO example



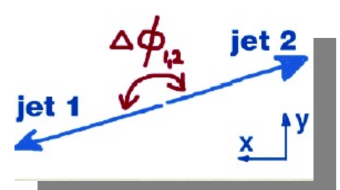
Benefits of NLO

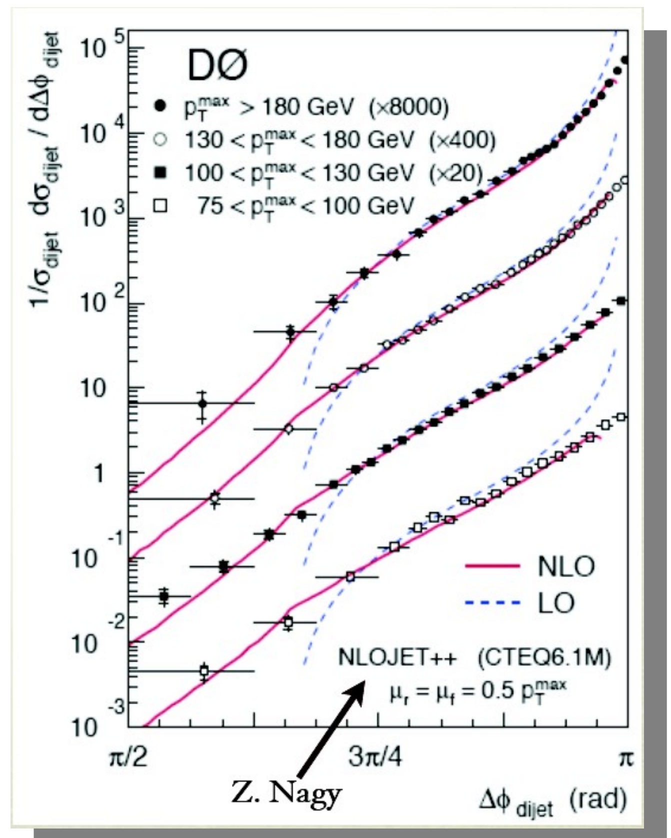
- Improved normalization and smaller residual uncertainty
- Better description of distribution shapes
- First serious quantitative prediction achieved only at NLO

W+jets

number of jets	CDF	LO	NLO
1	53.5 ± 5.6	$41.40(0.02)^{+7.59}_{-5.94}$	$57.83(0.12)^{+4.36}_{-4.00}$
2	6.8 ± 1.1	$6.159(0.004)^{+2.41}_{-1.58}$	$7.62(0.04)^{+0.62}_{-0.86}$
3	0.84 ± 0.24	$0.796(0.001)^{+0.488}_{-0.276}$	$0.882(0.005)^{+0.057}_{-0.138}$

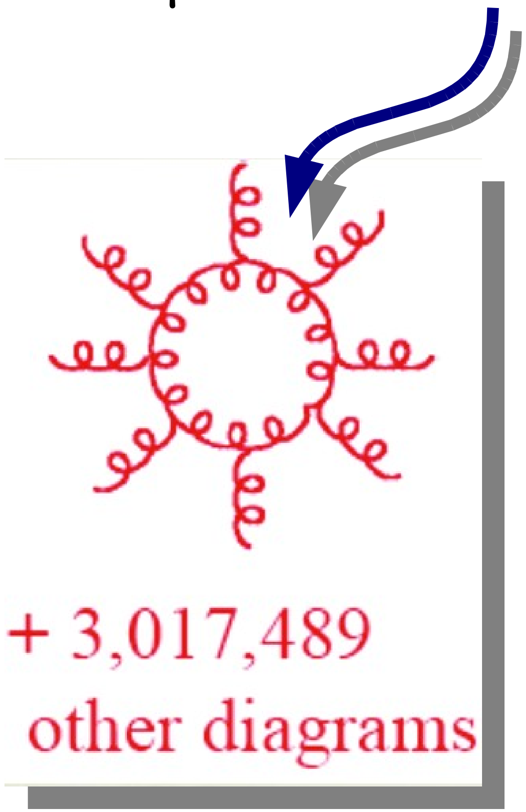
BLACKHAT: Berger et al., 0907.1984





NLO Difficulties

- NLO calculations become difficult for $2 \rightarrow 3$ processes and beyond...
- An example virtual correction:



Factorial growth of diagrams and enormous algebraic expressions, final results often simpler than intermediate steps

⇒ Need better organizing principle

Enabling Technology

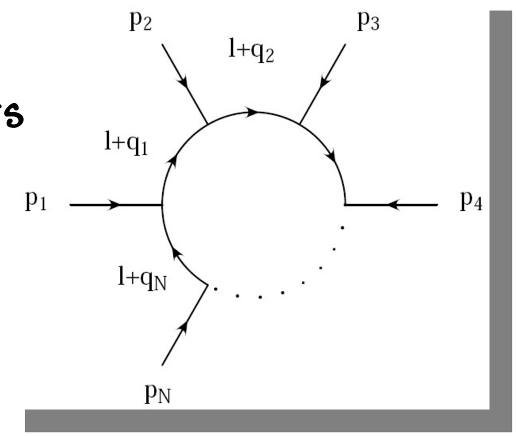
- An incredibly fast theory progress for fixed order NLO results with complicated final states. Key idea: obtain one-loop amplitudes using tree amplitudes

  - Generalized unitarity: Bern, Dixon, Dunbar, Kosower (1994); Britto, Cachazo, Feng (2004)
    any box integral reduction coefficient can be obtained from a quadrupole cut using complex momenta. One-loop amplitudes factorize into a product of four tree-amplitudes

  - The OPP method: Ossola, Papadopoulos, Pittau (2006)
    improved upon generalized unitarity and made it possible to combine speed and easiness

  - Rational parts of one-loop amplitudes from tree-amplitudes in multiple dimensions:
    Giele, Kunszt, Melnikov (2008)

- Feynman diagrammatic approach is still providing competitive results
  Bredenstein, Denner, Dittmaier, Kallweit, Pozzorini (2008-2011)



These ideas have been applied by several groups with an amazing outcome !

Enabling Technology

- Various packages exist for an automatic calculation of one-loop virtual corrections
  - BlackHat (unitarity and multiparticle cuts):
    Berger, Bern, Dixon, Febres Cordero, Ita, Kosower, Maitre (2008)
  - CutTools (reduction at integrand level): Ossola, Papadopoulos, Pittau (2007)
  - GOLEM (semi-numerical form factor decomposition):
    Binoth, Guillet, Heinrich, Pilon, Reiter (2008)
  - Rocket (generalized D-dim. unitarity): Ellis, Giele, Melnikov, Zanderighi (2008)
  - Samurai (generalized D-dim. Unitarity): Mastrolia, Ossola, Reiter, Tramontano (2010)

Enabling Technology

- NLO cross sections require real emission matrix elements and a way to extract their implicit IR poles:

$$\mathrm{d}\hat\sigma_{NLO} = \int_{\mathrm{d}\Phi_{m+1}} \left(\mathrm{d}\hat\sigma^{R}_{NLO} - \mathrm{d}\hat\sigma^{S}_{NLO}\right) + \int_{\mathrm{d}\Phi_{m}} \left(\int_1 \mathrm{d}\hat\sigma^{S}_{NLO} + \mathrm{d}\hat\sigma^{V}_{NLO} + \mathrm{d}\hat\sigma^{MF}_{NLO}\right)$$

Finite, can be integrated numerically — Integrated analytically

problem well understood at NLO with various methods:

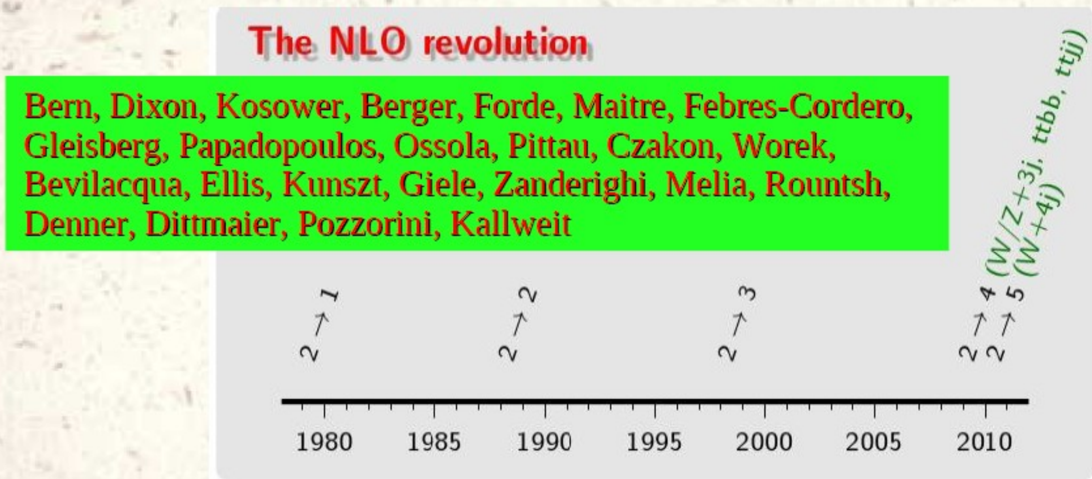
- Residue subtraction: Frixione, Kunszt, Signer
- Dipole subtraction: Catani, Seymour
- Antenna subtraction: Kosower; Campbell, Cullen, Glover; Daleo, Gehrmann, Maitre

and even automatized in various tools:

SHERPA (Gleisberg, Krauss); MadDipole (Frederix, Gehrmann, Greiner);
TeVJet (Seymour, Tevlin); Helac/Phegas (Czakon, Papadopouls, Worek);
MadFKS (Frederix, Frixione, Maltoni, Stelzer)

NEW: MadLoop: combines CutTools (virtual corrections) and MadFKS (real emission) into one automated package (Hirschi, Frederix, Frixione, Garzelli, Maltoni, Pittau)

An amazing theory progress



An experimenter's wishlist

- Hadron collider cross-sections one would like to know at NLO

Run II Monte Carlo Workshop, April 2001

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

$$pp \to W(Z)+3j$$

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

$$pp \to t\bar{t}jj$$

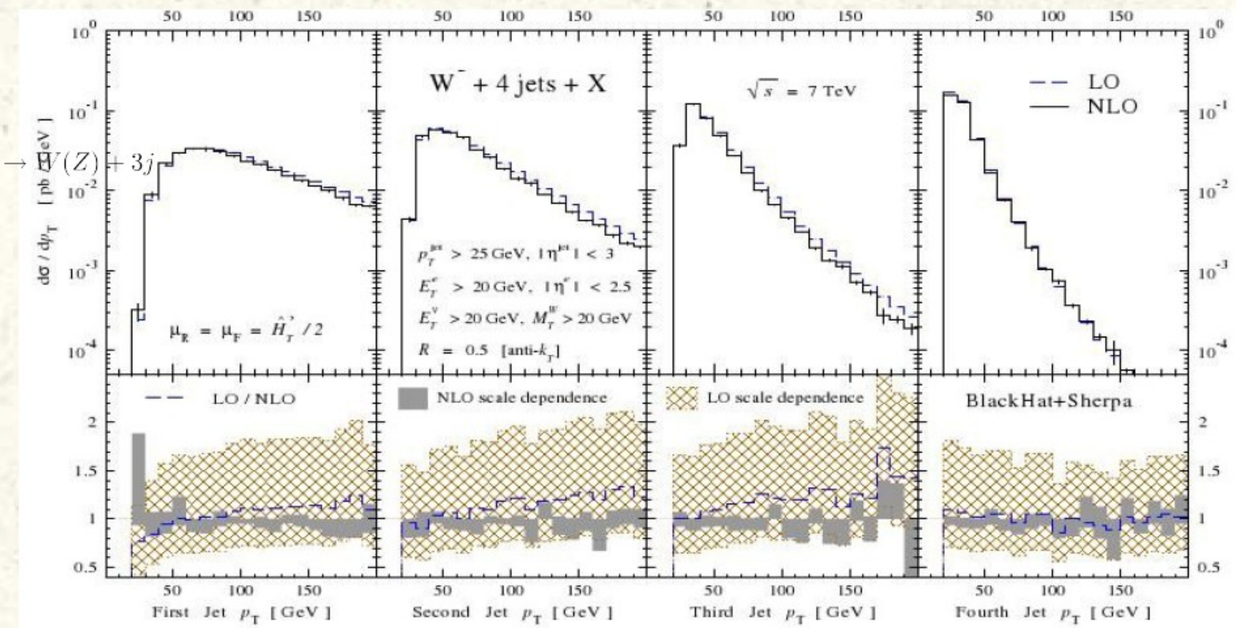
$$pp \to W^+W^+jj$$

$$pp \to W^+W^-b\bar{b}$$

$$pp \to W^+W^-jj$$

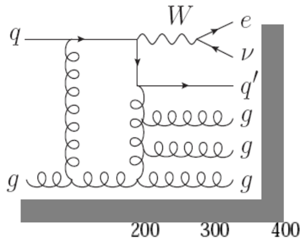
$$pp \to W+4j$$

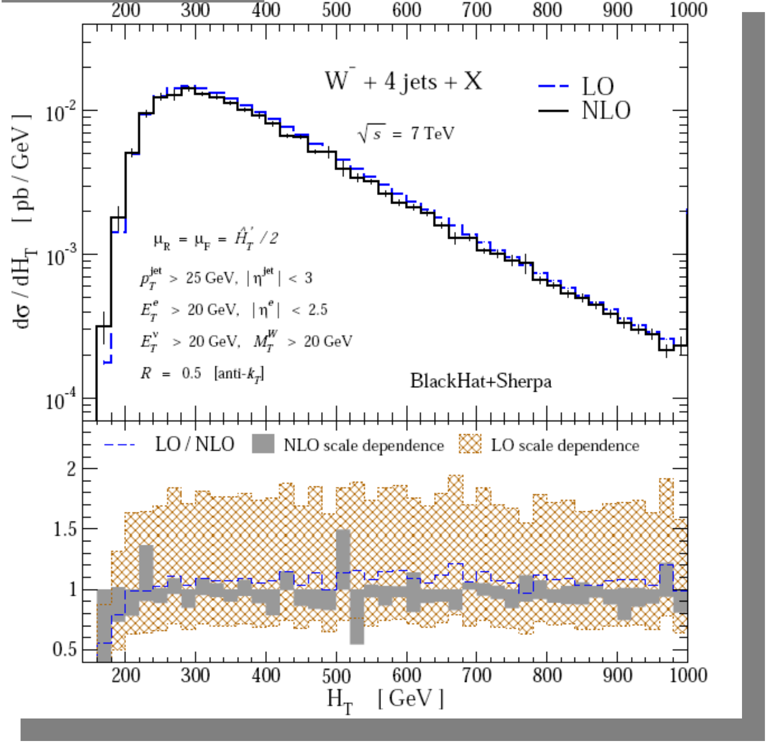
Blackhat collaboration, 2010



slide by K. Melnikov, LoopFest 2011

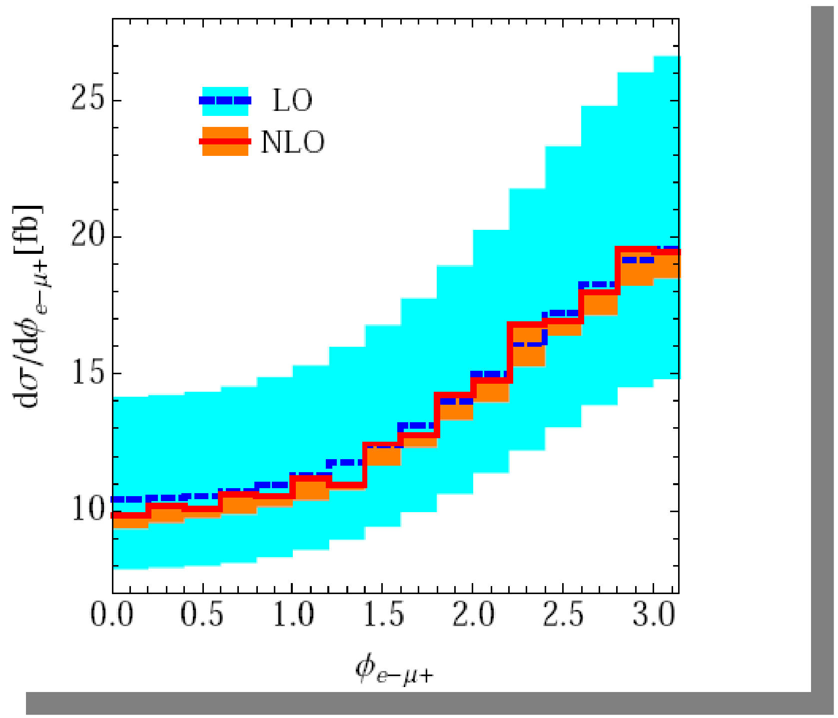
Selected Recent Highlights





Blackhat collaboration

W+W-jj



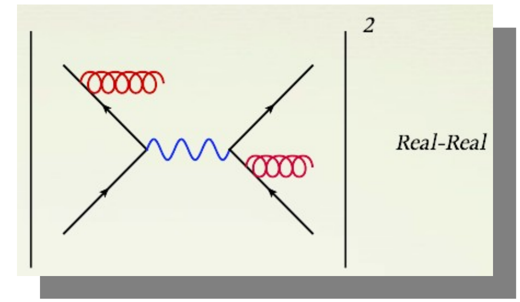
Melia, Melnikov, Rontsch, Zanderighi

- Significant reduction of scale variation from NLO result
  → Important when searching for new physics especially SUSY

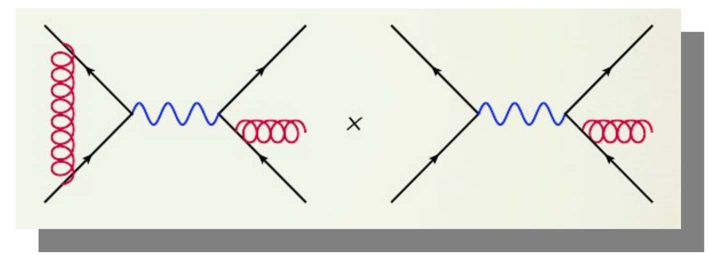
- Opening angle between leptons in W+W-jj used to distinguish Higgs from background.
  → Significant reduction of scale dependence when NLO result is included

Computing Cross Sections: NNLO and beyond

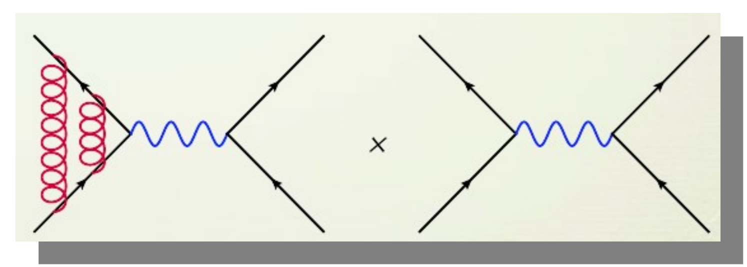
$$\sigma = \overbrace{\sigma_0}^{LO} + \overbrace{\frac{\alpha_s}{\pi}\sigma_1}^{NLO} + \overbrace{\left(\frac{\alpha_s}{\pi}\right)^2\sigma_2}^{NNLO} + \dots$$



- When is NNLO needed?
  - When NLO corrections are large and NNLO is needed to check expansion (gg → H is an example)
  - For benchmark processes where high precision is needed (Drell-Yan for PDFs, e+e- → 3 jets for strong coupling constant,...)



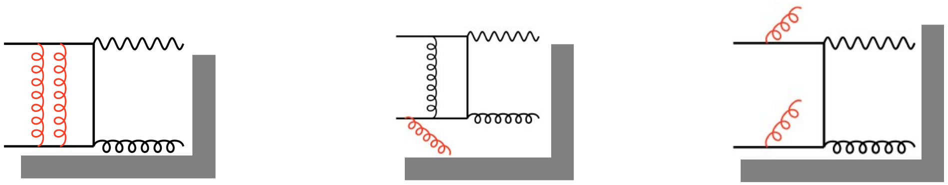
real-virtual



virtual-virtual

Enabling Technology

- Jet cross sections calculation at NNLO is possible if two ingredients are available:
  - two-loop matrix elements
  - a subtraction method for implicit IR singularities from real radiation



- Two-loop matrix elements known for two-jet production, vector-boson-plus- jet production and (2+1) jet production in DIS
  (Anastasiou, Glover, Oleari, Tejeda-Yeomans; Bern, de Freitas, Dixon; Gehrmann, Remiddi; Glover, Gehrmann)

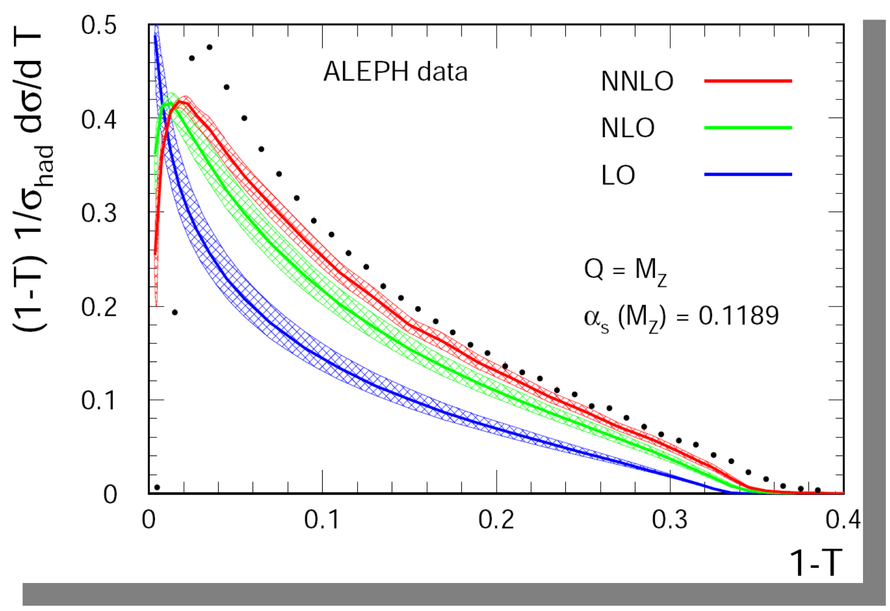
- Antenna subtraction: a process independent analytical method successfully applied to e+e- → 3jets
  - → final-final antennae (A. Gehrmann, T. Gehrmann, N. Glover 2005)
  - extended to initial-final configuration (A. Daleo, A. Gehrmann, T. Gehrmann, N. Glover, G. Luisoni 2010)
  - first results for initial-initial configuration (R. B., A. Gehrmann, M. Ritzmann 2010). Other missing initial-initial antennae are in progress

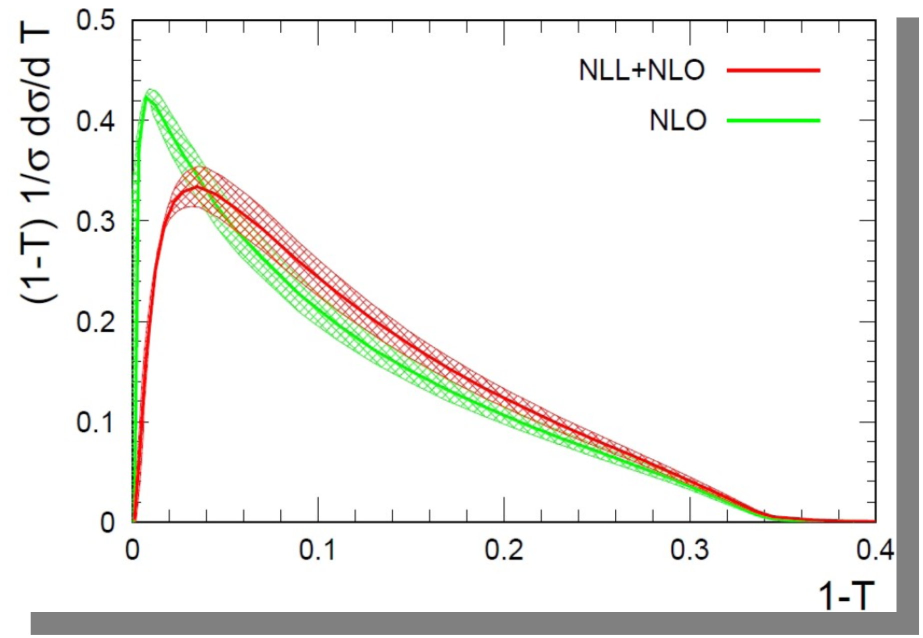
- Sector decomposition: relies on numerical integration of subtraction terms; many successful applications
  (Binoth, Heinrich 2002; Anastasiou, Melnikov, Petriello 2003)
  - Recent deveopments suggested a way of making this method process independent (Czakon 2010)

- qT subtraction for specific hadron collider processes (Catani, Grazzini 2007)

NNLO and Beyond: the Strong Coupling Constant

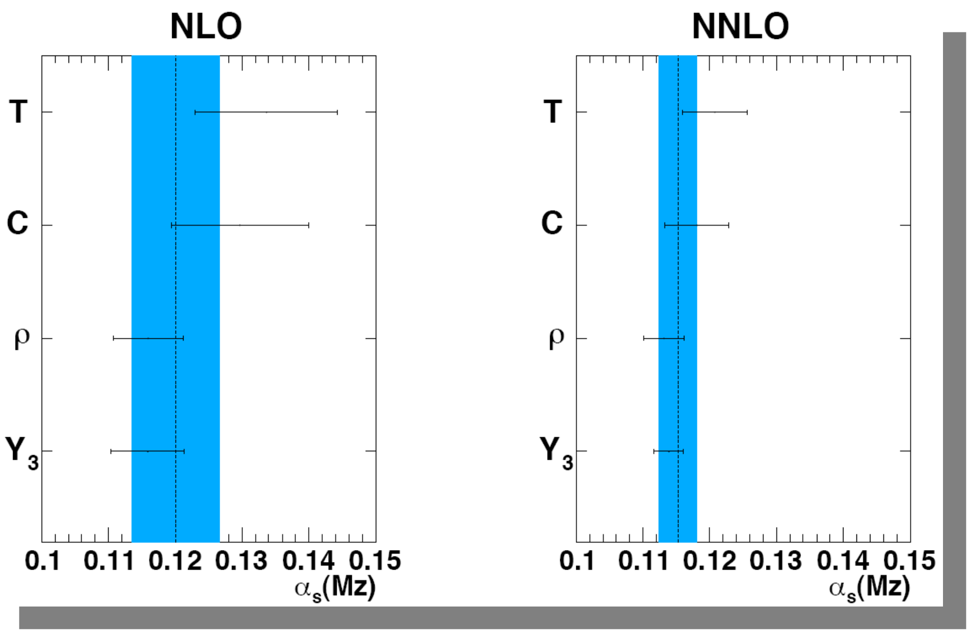
- Precise extractions of $\alpha_s(M_Z)$ are obtained from event shapes from LEP and other experments



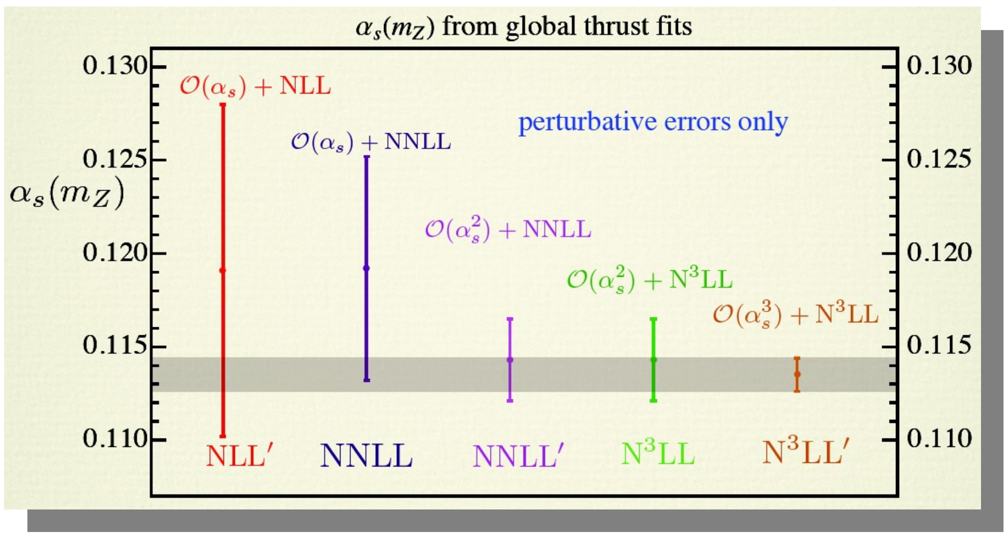


- Accurate determination of $\alpha_s(M_Z)$ requires both fixed higher-order results and resummation of large Thrust logarithms $\rightarrow \alpha_s \log \frac{1}{1-T} \simeq 1$ in the limit $T \rightarrow 1$

Strong Coupling Constant Extraction



A. Gehrmann, T. Gehrmann, N. Glover, G. Heinrich



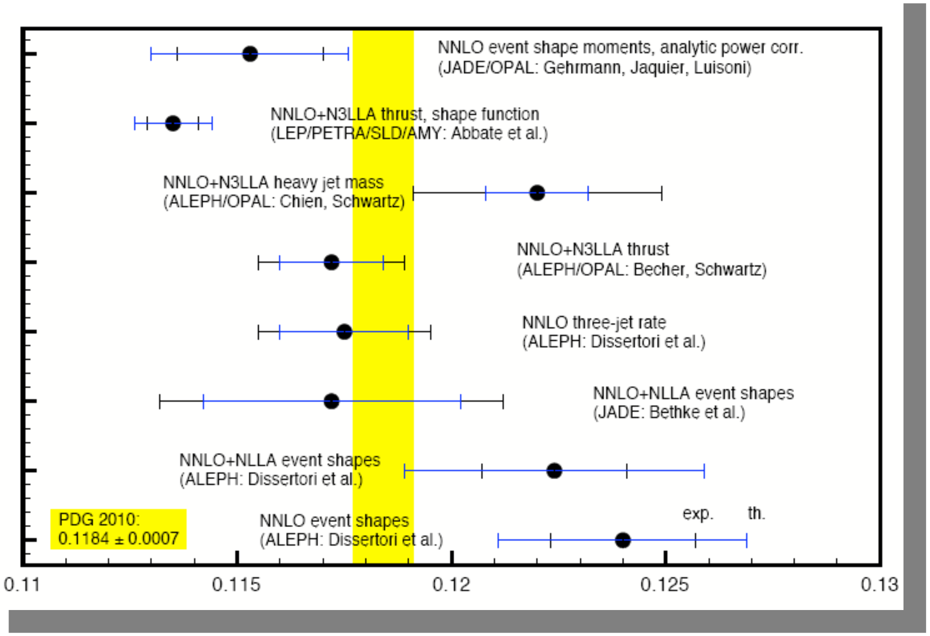
Abbate, Fickinger, Hoang, Mateu, Stewart

- $O(\alpha_s^3)$ correction to e+ e- → 3 jets completed (A. Gehrmann, T. Gehrmann, N. Glover, G. Heinrich; S. Weinzierl)
- Resummation through N^3LL available and theory uncertainty is under good control

  (Abbate @ al; Becher @ al; Chien @ al; ....)

- This work leads directly to a reduced uncertainty on the extraction of the strong coupling

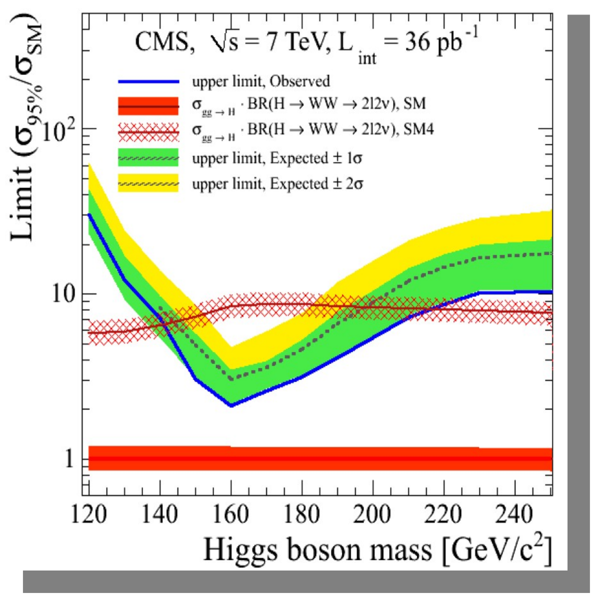
Strong Coupling Constant Extraction

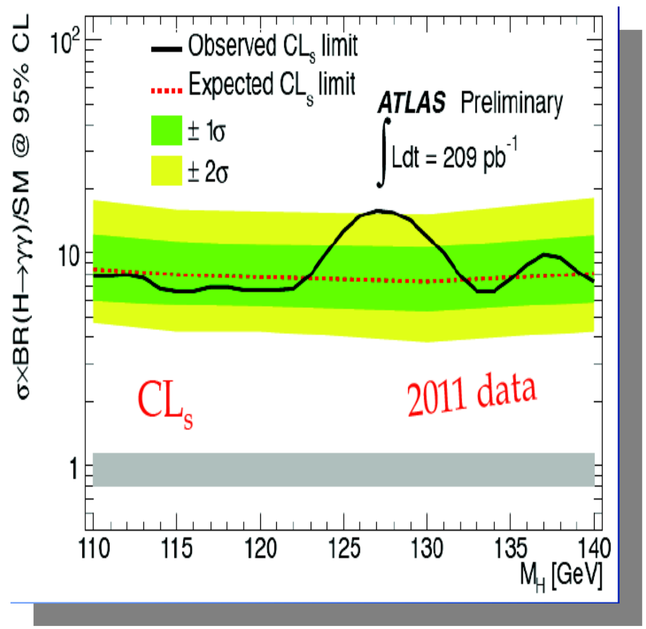


- Compilation of $\alpha_s(M_Z)$ values based on results for:
  - e+ e- $\rightarrow$ 3 jets through NNLO in α_s
  - resummation of thrust logarithms trough N^3LL
  - mostly LEP data

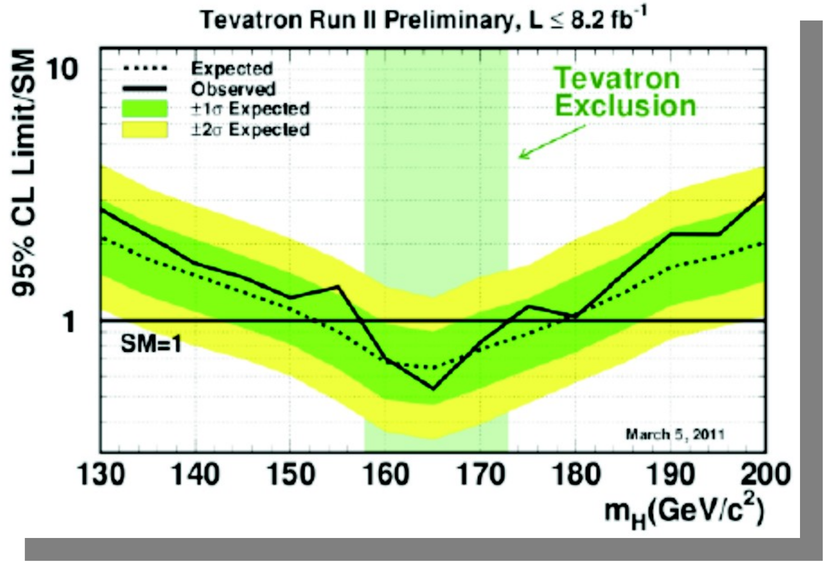
Survey of Experimental Results for Higgs

- Amazing recent activity at Tevatron and LHC on Higgs searches

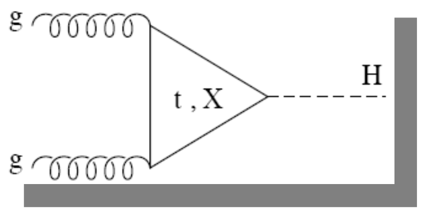




Lets look at the theory going into these plots



Theory status for gg → H in the SM

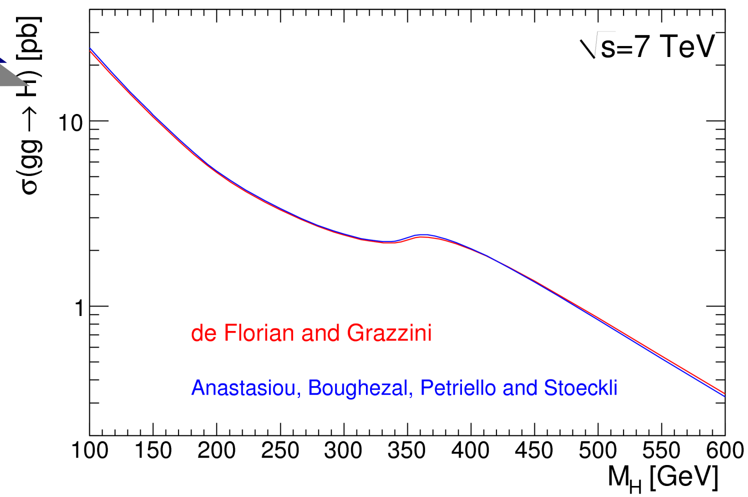


- Higgs production via gluon fusion: dominant mode at LHC and Tevatron

- Inclusive cross section for gg → H is under good theoretical control following different approaches

  - Results based on:

    - Exact NLO QCD corrections for top and bottom diagrams
    - NNLO and NNLL in the large mT limit
      (Harlander, Kilgore; Anastasiou, Melnikov; Ravindran,Smith, van Neerven; Catani, de Florian, Grazzini)
    - EW corrections in the complex mass scheme
      (Actis, Passarion, Sturm, Uccirati 2008)
    - mixed QCD-EW corrections
      (Anastasiou, R. B., Petriello 2009)
    - MSTW2008 PDFs as well as results following the PDF4LHC working group recommendations



CERN Yellow Report 2011

- Exclusive calculations through NNLO for H → $\gamma\gamma$
  $H \rightarrow WW \rightarrow l\,l\,\nu\,\bar{\nu}$, H → Z Z → 4 leptons
  (Anastasiou, Melnikov, Petriello 2005; Catani, Grazzini 2008)

Looking beyond the SM with the Higgs

- New states can significantly modify the properties of the Higgs
  - squark/gluino loops

    Anastasiou, Beerli, Daleo (2008); Muehlleitner, Rzehak, Spira (2008)

  - Extra heavy quark families

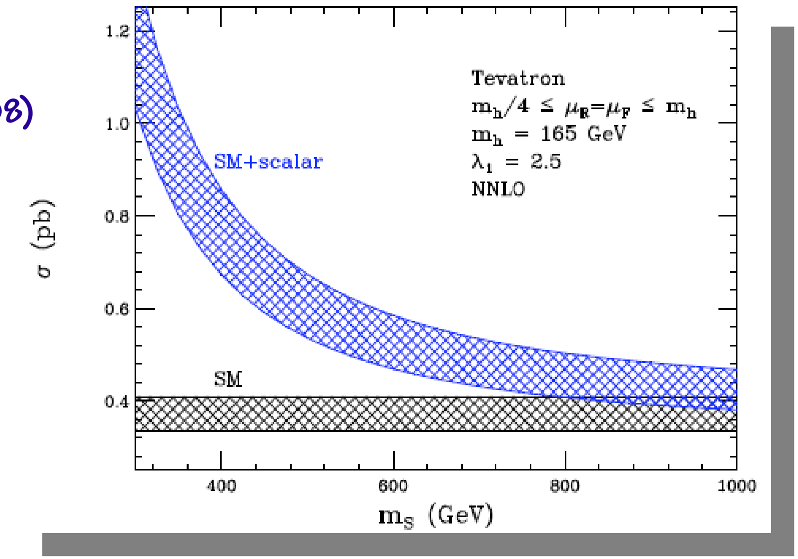
    (Anastasiou, R. B., Furlan 2010)

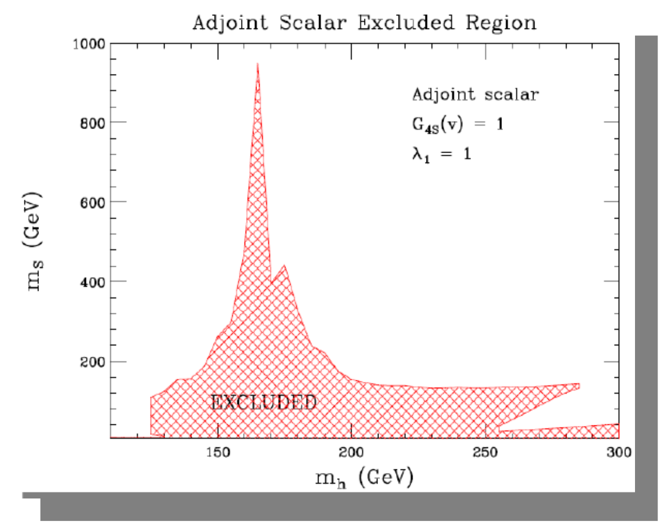
  - Color octet scalars

    (R. B., Petriello 2010)

  - Using the calculated signal and branching ratio in the presence of new states and the Tevatron bounds on $\sigma(g\,g \to H) \times Br(H \to WW)$

    strong bounds on the parameter space of new physics can be obtained.





R. B.

Conclusions

- Much better prepared for the flood of LHC data than expected several years ago
- Multiple NLO methods producing quick results
- W+ 3 jets, W+ 4 jets now known at NLO: an incredible achievement
- Strong coupling constant extracted with NNLO precision: an important input parameter to many LHC studies
- Theory for the Higgs is known to NNLO and beyond; cross section errors under good control