Perturbative QCD
&
The LHC

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Present status of QCD

✓ Thanks to LEP, Hera, and Tevatron QCD today *firmly established*

✓ Despite temporary discrepancies, theory successful in describing experimental data, currently *no major area of discrepancy*

✗ However, the LHC brings a *new frontier in energy and luminosity*

✗ Main goals of the LHC:

- ☛ discovery of the Higgs and New Physics
- ☛ identification of New Physics (requires precision measurements)

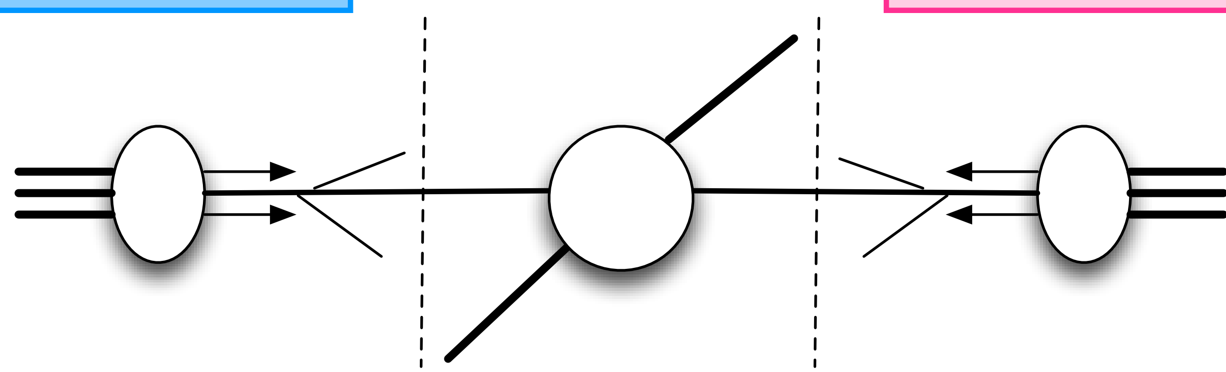
Do we master QCD well enough to guarantee a successful physics program in this new regime?

Prerequisite: factorization

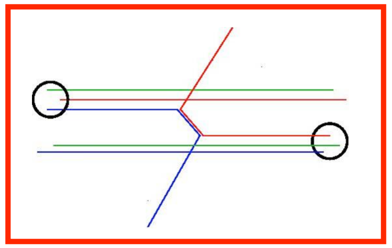
$$\frac{d\sigma_{\mathrm{pp}\to\mathrm{hadrons}}}{dX} = \sum_{a,b} \int dx_1 dx_2 f_a(x_1,\mu_F) f_b(x_2,\mu_F) \times \frac{d\hat{\sigma}_{\mathrm{ab}\to\mathrm{partons}}(\alpha_s(\mu_R),\mu_R,\mu_F)}{dX} + \mathcal{O}\left(\frac{\Lambda^n_{\mathrm{QCD}}}{Q^n}\right)$$

Extracted from data, but evolution is perturbative

Expansion in the coupling constant (LO, NLO, NNLO...)



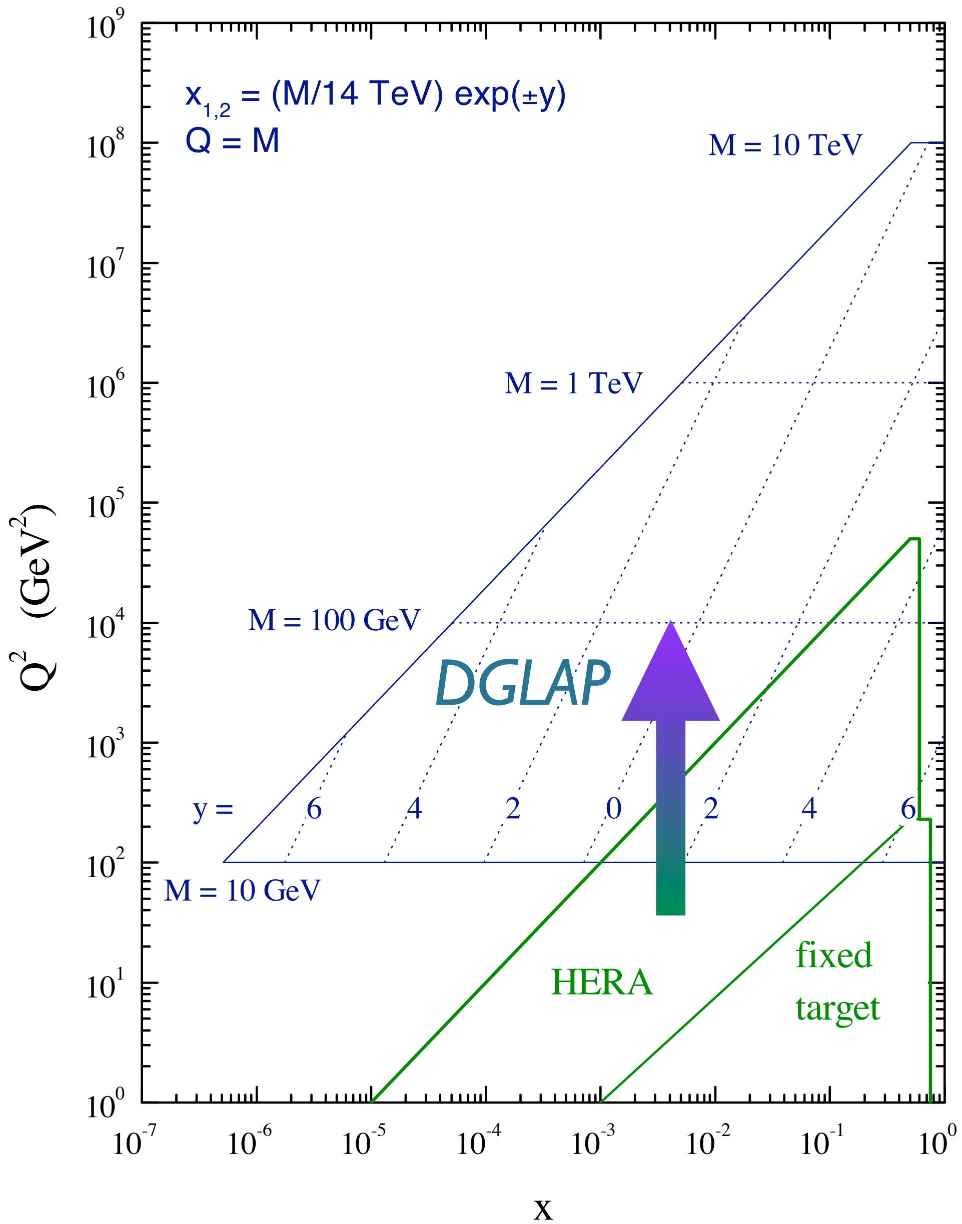
NB: factorization used in many contexts without proof



Parton densities coverage

- most of the LHC x-range covered by Hera
- need 2-3 orders of magnitude Q^2-evolution
- rapidity distributions probe extreme x-values
- 100 GeV physics at LHC: small-x, sea partons
- TeV physics: large x

LHC parton kinematics



PDF summary report, Hera-LHC '05

➠ *Hera: key and essential input to the LHC* *[see talk of A. Raval]*

Parton densities: recent progress

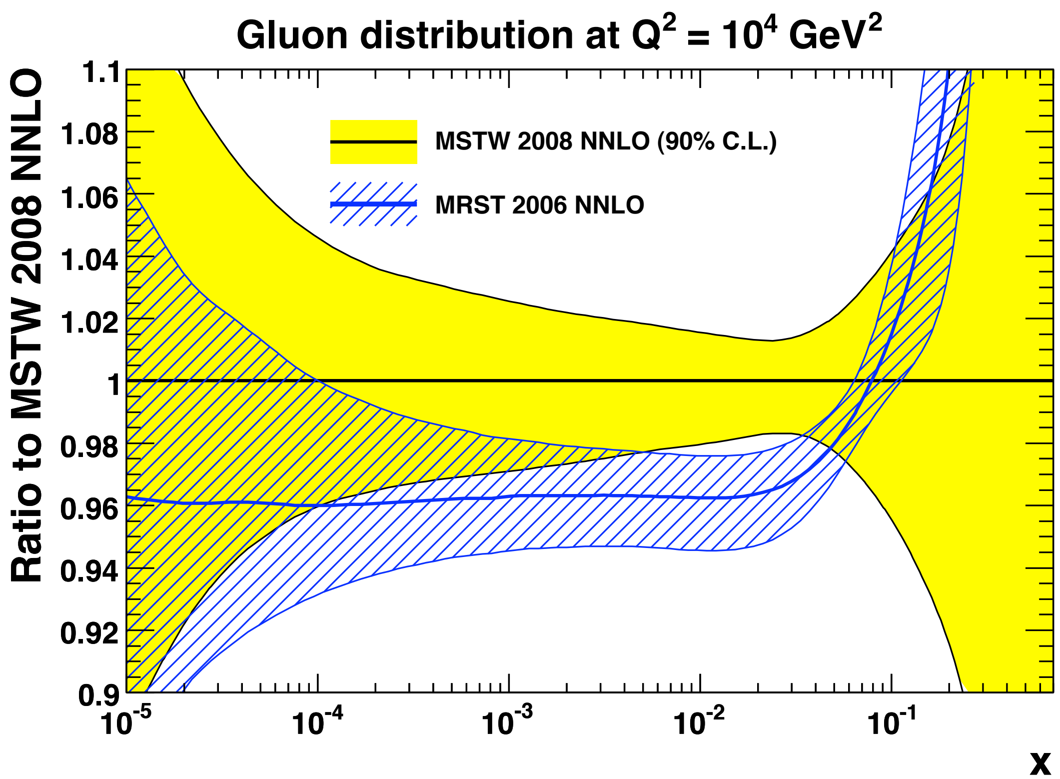
Recent major progress:

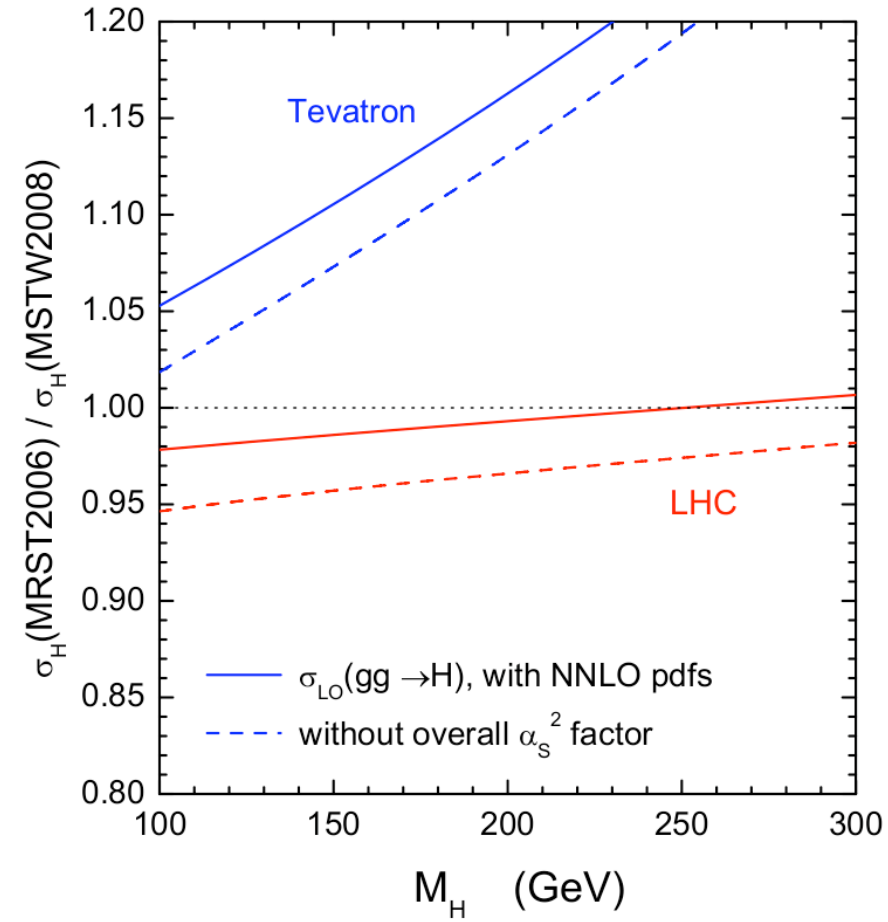
- full NNLO evolution (previous approximate NNLO)
- full treatment of heavy flavors near the quark mass

  [Numerically: e.g. (6-7)% effect on Drell-Yan at LHC]
- more systematic use of uncertainties/correlations (e.g. dynamic tolerance, combinations of PDF + α_s uncertainty)
- Neural Network (NN) PDFs

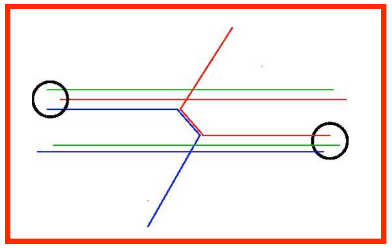
splitting functions at NNLO: Moch, Vermaseren, A.Vogt '04
[+ much related theory progress '04 -'08]
Alekhin, CTEQ, MSTW (new MSTW08), NN collaboration

Implications of MSTW2008



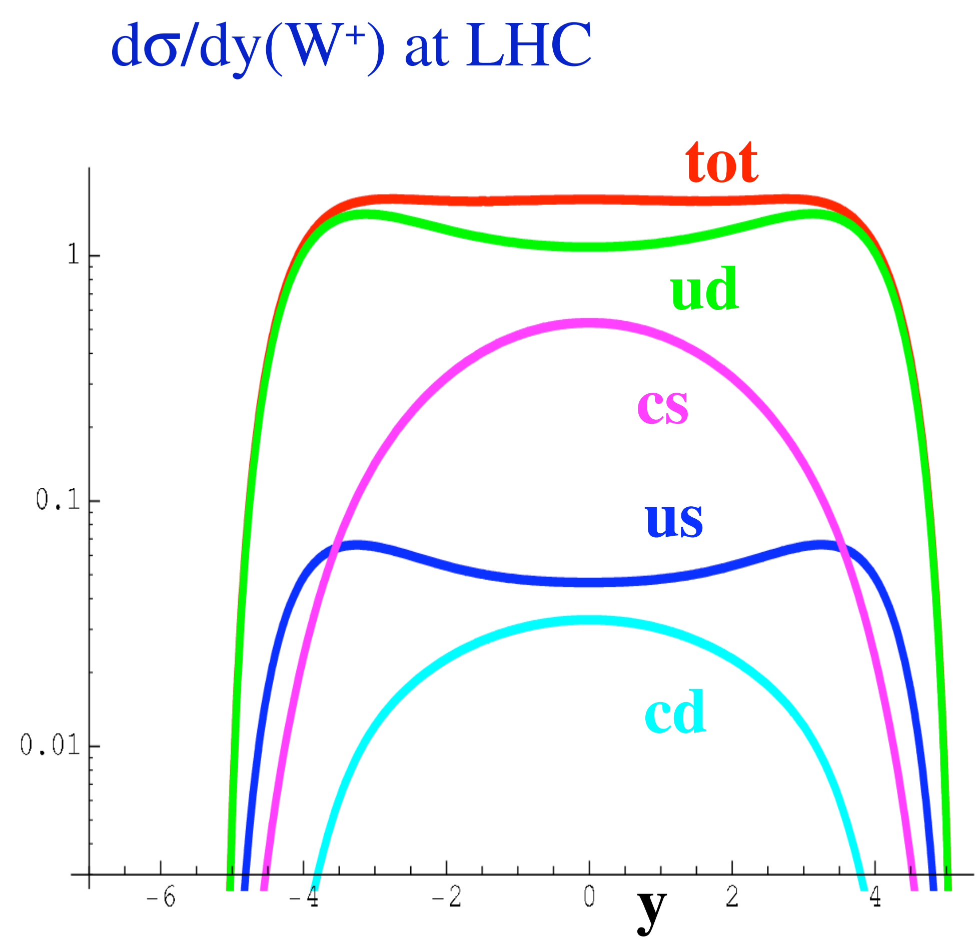


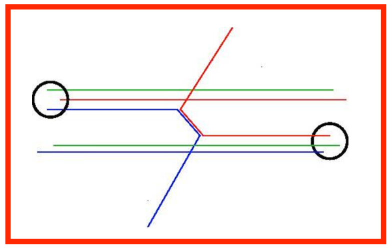
- ☛ smaller '08 gluon at large x higher at small x (momentum sum rule)
- ☛ Higgs cross-section smaller at the Tevatron with new '08 PDFs



Parton densities: some open issues

- heavy quark treatment
  theoretically not 'clean' (various schemes, ad hoc procedures), but very important at the LHC





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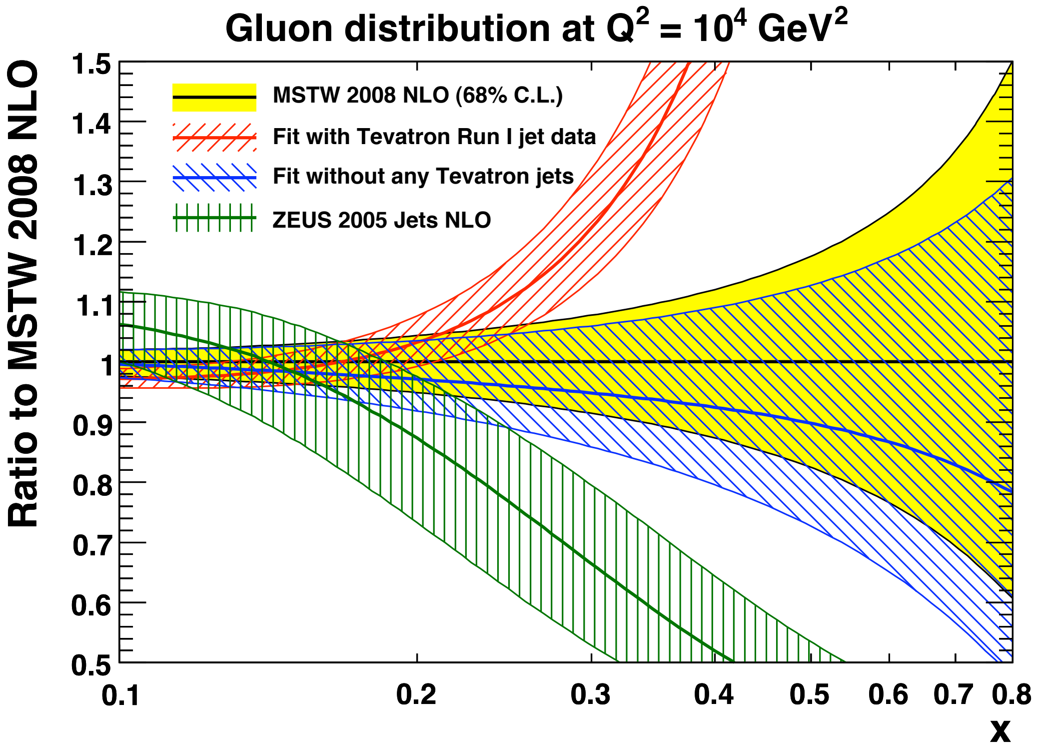

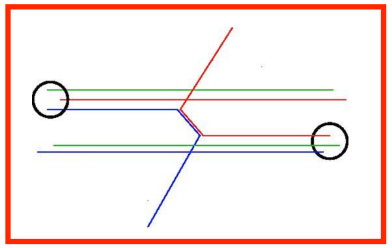

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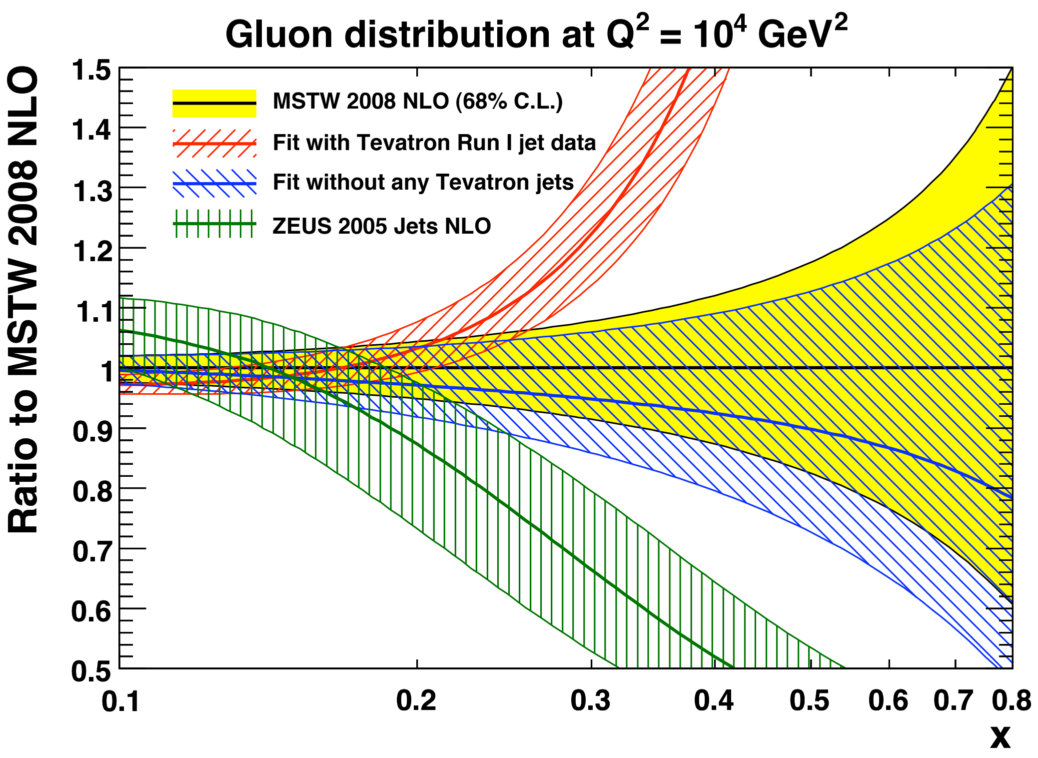

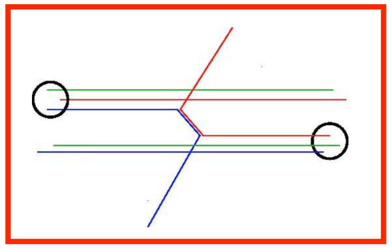

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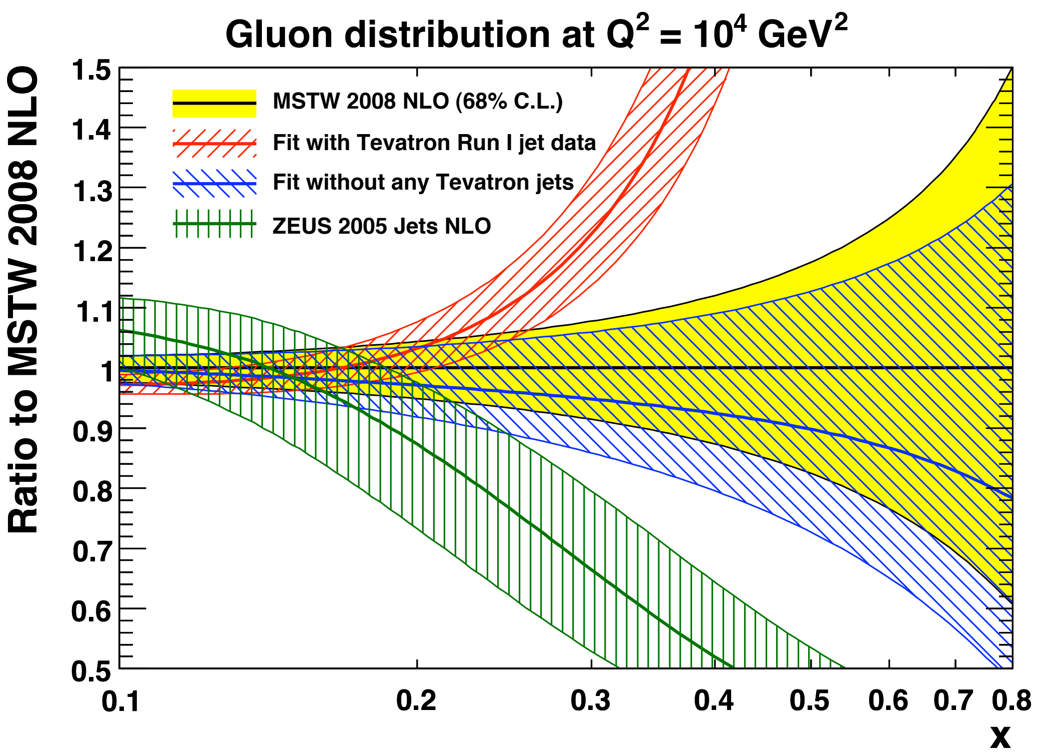
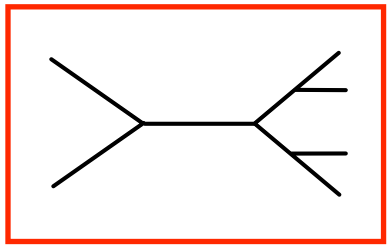


⇒ Description of PDFs reaching precision, but still some work ahead

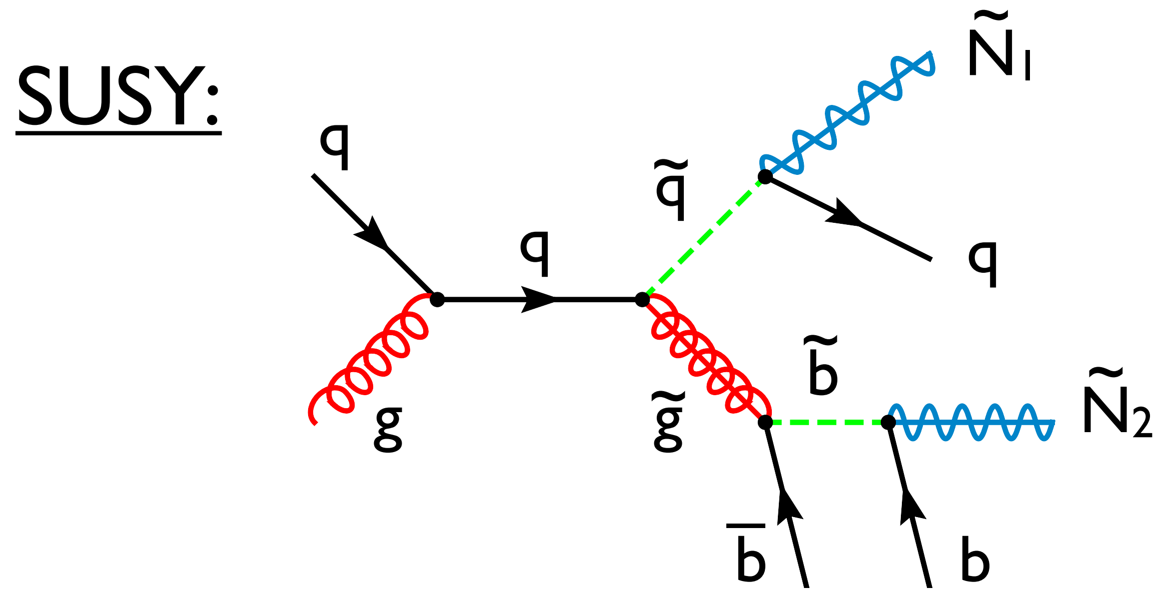


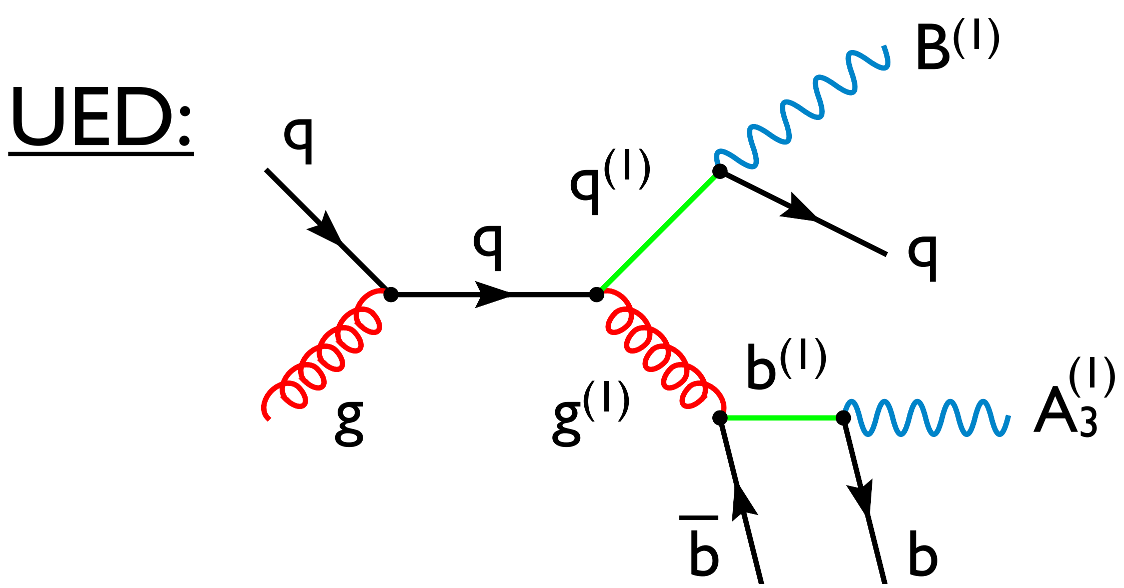
Multiparticle final states

<u>The LHC will operate in a new regime</u>: highest energy & luminosity

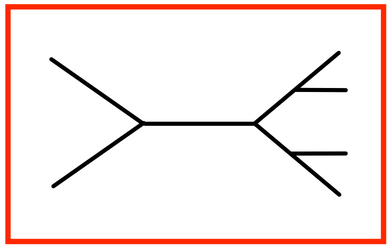
Very large number of high-multiplicity events

- typical SM process is accompanied by radiation multi-jet events
- most signals involve pair-production and subsequent chain decays





More important than ever to describe high-multiplicity final states



Leading order

Status: fully automated, at most 8 outgoing particles

Alpgen, CompHEP, CalcHEP, Helac, Madgraph, Helas, Sherpa, Whizard, ...

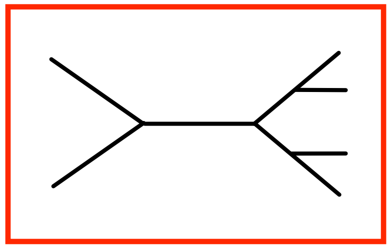
Drawbacks of LO: large scale dependences, sensitivity to cuts, poor modeling of jets, ...

Example: W+4 jet cross-section $\propto \alpha_s(Q)^4$

Vary $\alpha_s(Q)$ by ±10% via change of Q ⇒ cross-section varies by ±40%

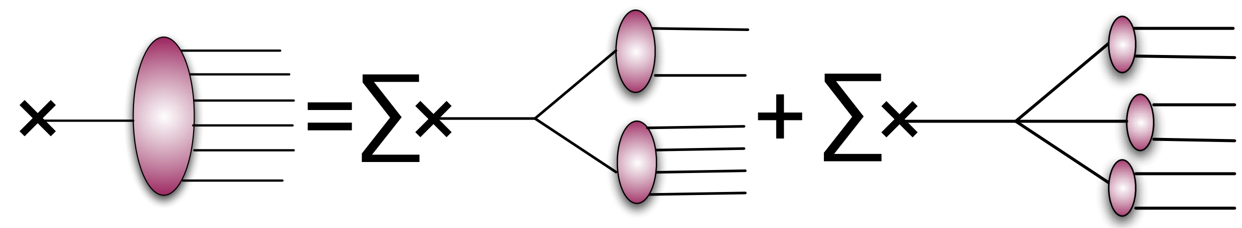
Why use LO at all?

- fastest option; often the only one
- test quickly new ideas with fully exclusive description
- many working, well-tested approaches
- highly automated, crucial to explore new ground, but no precision



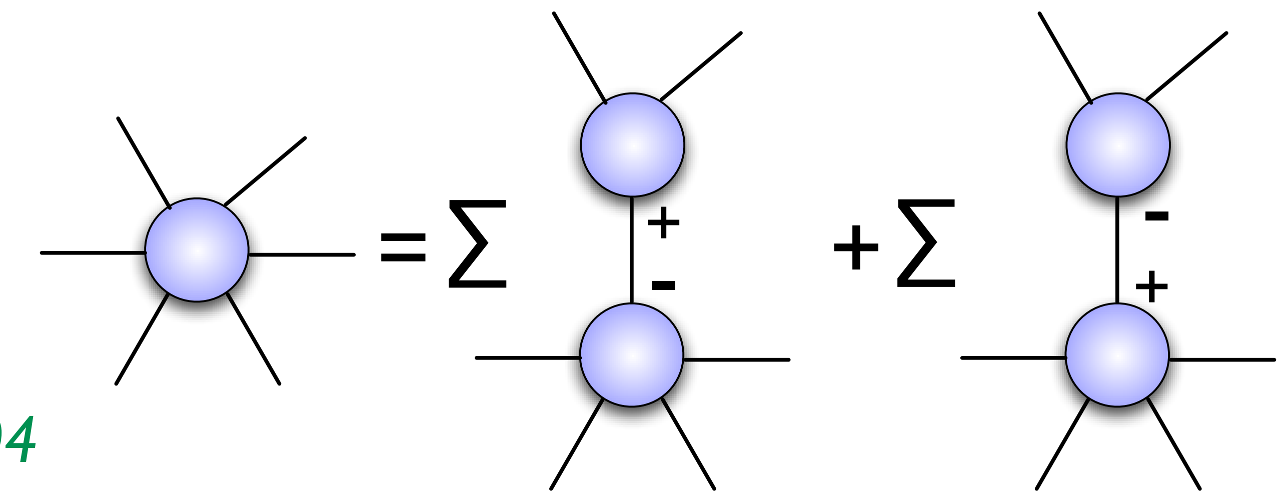
LO: 3 methods beyond Feynman

✓ Berends-Giele relations: compute helicity amplitudes recursively using off-shell currents



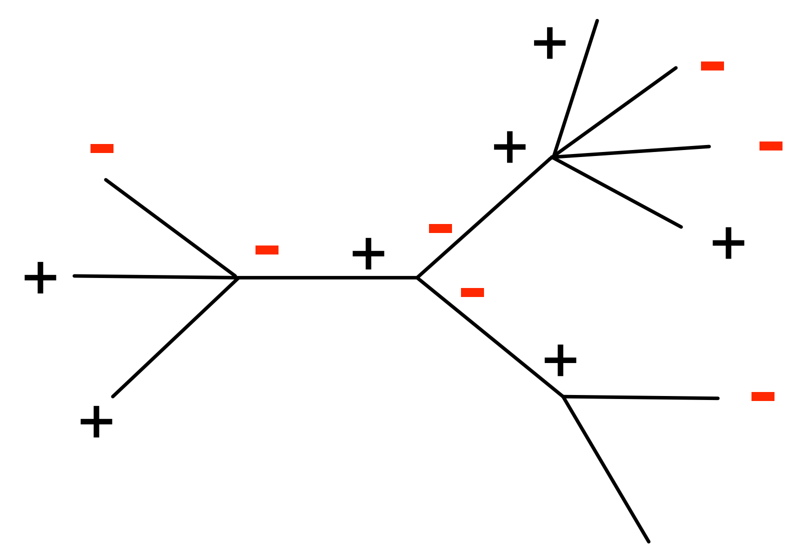
Berends, Giele '88

✓ BCF relations: compute helicity amplitudes via on-shell recursions (use complex momentum shifts)

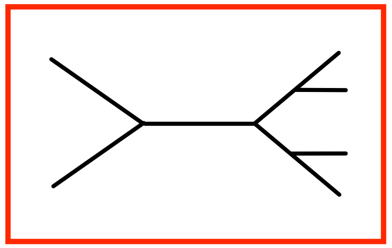


Britto, Cachazo, Feng '04

✓ CSW relations: compute helicity amplitudes by sewing together MHV amplitudes [- - + + ... +]



Cachazo, Svrcek, Witten '04



LO race: who is faster?

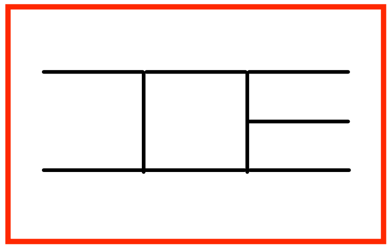
Duhr et al. '06
also Dinsdale et al. '06

Time [s] for 2 → n gluon amplitudes for 10^4 points

Final state	BG	BCF	CSW
2g	0.28	0.33	0.26
3g	0.48	0.51	0.55
4g	1.04	1.32	1.75
5g	2.69	7.26	5.96
6g	7.19	59.1	30.6
7g	23.7	646	195
8g	82.1	8690	1890
9g	270	127000	29700
10g	864	-	-

☛ numerical superiority of traditional Berends-Giele methods

See next talk by Frank Krauss for tools and phenomenological applications of LO



Next-to-leading order

For precision studies need next-to-leading-order

because the coupling is not so small, to reduce dependence from unphysical scales, to model jets better, to predict the normalization, ...

<u>Status of NLO:</u>

☑ 2 → 2: all known or easy in SM and beyond

☑ 2 → 3: very few processes not yet computed

[but: often no decays, newest codes mostly private]

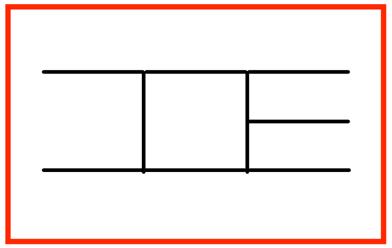
☐ 2 → 4: barely touched ground [pp → $t\bar{t}\, b\bar{b}$, pp → W+3jets]

Bredenstein et al. '08,'09; Berger et al. '09; Ellis et al. '09

<u>Cancelation of divergences</u>: automated subtraction

Gleisberg, Krauss '07; Seymour, Tevlin '08; Hasegawa et al. '08; Fredrix et al. '08

<u>Bottleneck up to recently:</u> virtual, loop amplitudes

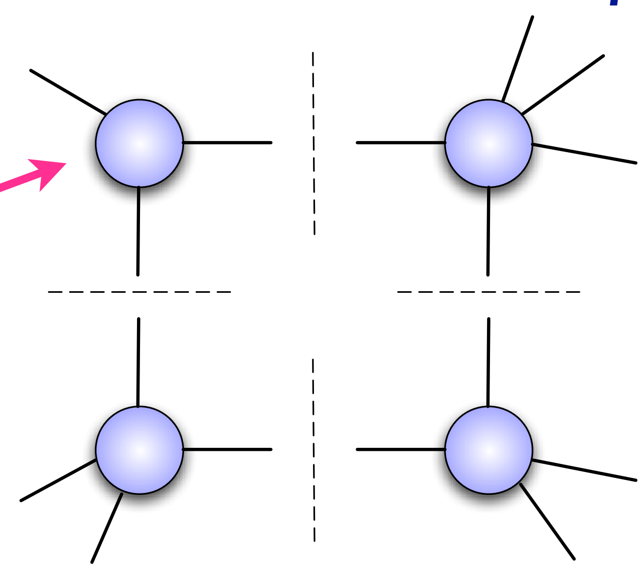


Two breakthrough ideas for NLO

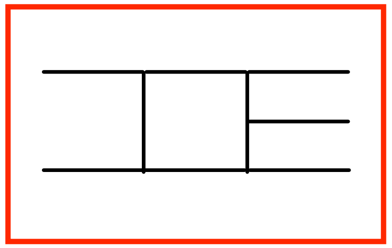
Aim: NLO loop integral without doing the integration

1) "... we show how to use generalized unitarity to read off the (box) coefficients. The generalized cuts we use are quadrupole cuts ..."

NB: non-zero because cut gives complex momenta



Britto, Cachazo, Feng '04

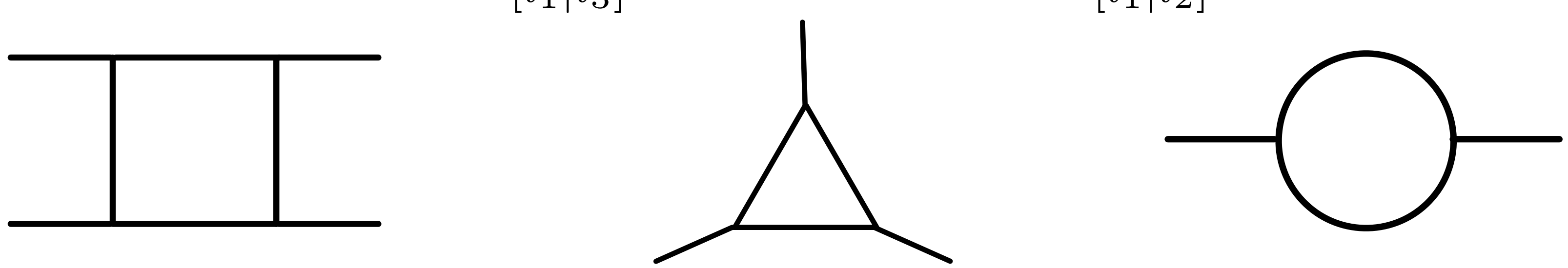


Two breakthrough ideas

Aim: NLO loop integral without doing the integration

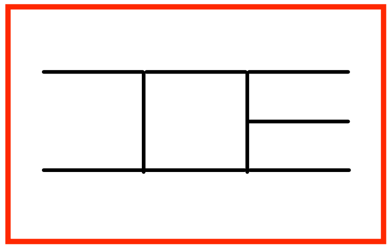
2) The OPP method: "We show how to extract the coefficients of 4-, 3-, 2- and 1-point one-loop scalar integrals...."

$$\mathcal{A}_N = \sum_{[i_1|i_4]} \left(d_{i_1 i_2 i_3 i_4} \; I^{(D)}_{i_1 i_2 i_3 i_4} \right) + \sum_{[i_1|i_3]} \left(c_{i_1 i_2 i_3} \; I^{(D)}_{i_1 i_2 i_3} \right) + \sum_{[i_1|i_2]} \left(b_{i_1 i_2} \; I^{(D)}_{i_1 i_2} \right) + \mathcal{R}$$



rational part treated separately

Ossola, Pittau, Papadopolous '06

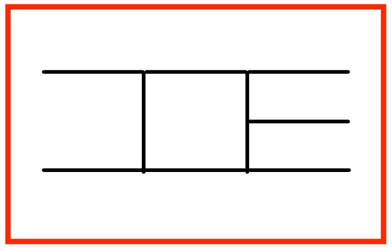


The 2005 Les Houches wishlist

QCD, EW & Higgs Working group report '06

Table 42: The LHC "priority" wishlist for which a NLO computation seems now feasible.

process ($V \in \{Z, W, \gamma\}$)	relevant for
1. $pp \to V\,V$ jet	$t\bar{t}H$, new physics
2. $pp \to t\bar{t}\,b\bar{b}$	$t\bar{t}H$
3. $pp \to t\bar{t} + 2$ jets	$t\bar{t}H$
4. $pp \to V\,V\,b\bar{b}$	VBF$\to H \to VV$, $t\bar{t}H$, new physics
5. $pp \to V\,V + 2$ jets	VBF$\to H \to VV$
6. $pp \to V + 3$ jets	various new physics signatures
7. $pp \to V\,V\,V$	SUSY trilepton



The 2007 update

NLO multi-leg Working group report '08

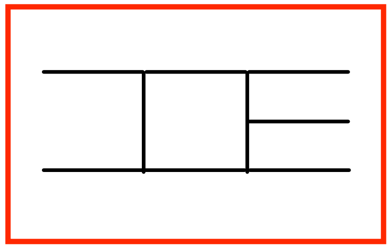
Process ($V \in \{Z, W, \gamma\}$)	Comments
Calculations completed since Les Houches 2005	
1. $pp \to VV$jet	WWjet completed by Dittmaier/Kallweit/Uwer [3]; Campbell/Ellis/Zanderighi [4] and Binoth/Karg/Kauer/Sanguinetti (in progress)
2. $pp \to$ Higgs+2jets	NLO QCD to the gg channel completed by Campbell/Ellis/Zanderighi [5]; NLO QCD+EW to the VBF channel completed by Ciccolini/Denner/Dittmaier [6, 7]
3. $pp \to V\,V\,V$	ZZZ completed by Lazopoulos/Melnikov/Petriello [8] and WWZ by Hankele/Zeppenfeld [9]
Calculations remaining from Les Houches 2005	
4. $pp \to t\bar{t}\,b\bar{b}$	relevant for $t\bar{t}H$
5. $pp \to t\bar{t}$+2jets	relevant for $t\bar{t}H$
6. $pp \to V\,V\,b\bar{b}$,	relevant for VBF $\to H \to VV$, $t\bar{t}H$
7. $pp \to V\,V$+2jets	relevant for VBF $\to H \to VV$ VBF contributions calculated by (Bozzi/)Jäger/Oleari/Zeppenfeld [10–12]
8. $pp \to V$+3jets	various new physics signatures
NLO calculations added to list in 2007	
9. $pp \to b\bar{b}b\bar{b}$	Higgs and new physics signatures
Calculations beyond NLO added in 2007	
10. $gg \to W^*W^*$ $\mathcal{O}(\alpha^2\alpha_s^3)$	backgrounds to Higgs
11. NNLO $pp \to t\bar{t}$	normalization of a benchmark process
12. NNLO to VBF and Z/γ+jet	Higgs couplings and SM benchmark
Calculations including electroweak effects	
13. NNLO QCD+NLO EW for W/Z	precision calculation of a SM benchmark

} based on Feynman diagrams; private codes only

← '09 with standard techniques (4. $pp \to t\bar{t}\,b\bar{b}$)

← '09 with new techniques (8. $pp \to V$+3jets)

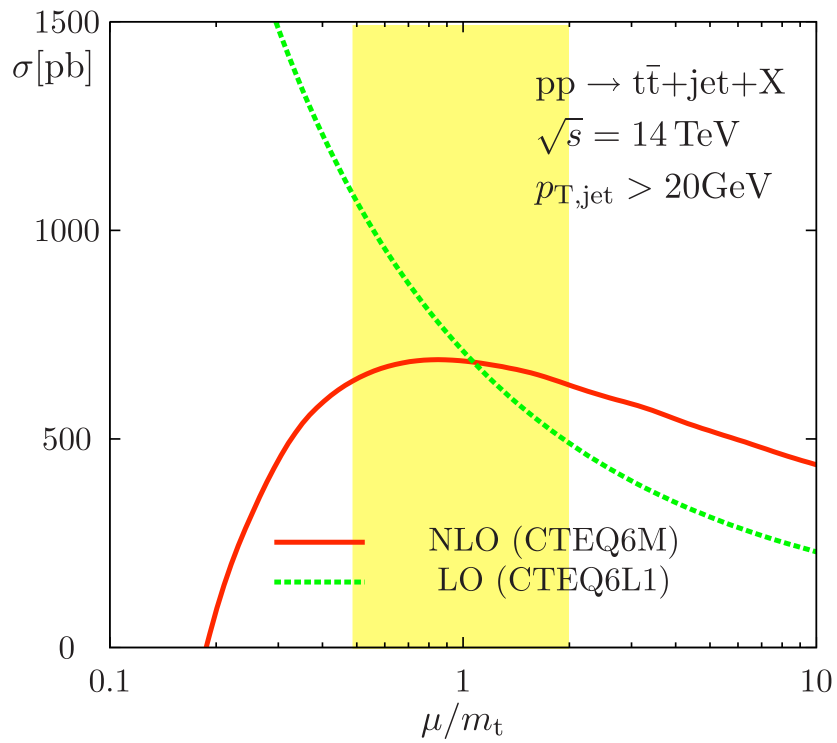
+ virtual amplitudes for several of those processes *[van Hameren, Papadopoulos, Pittau]*

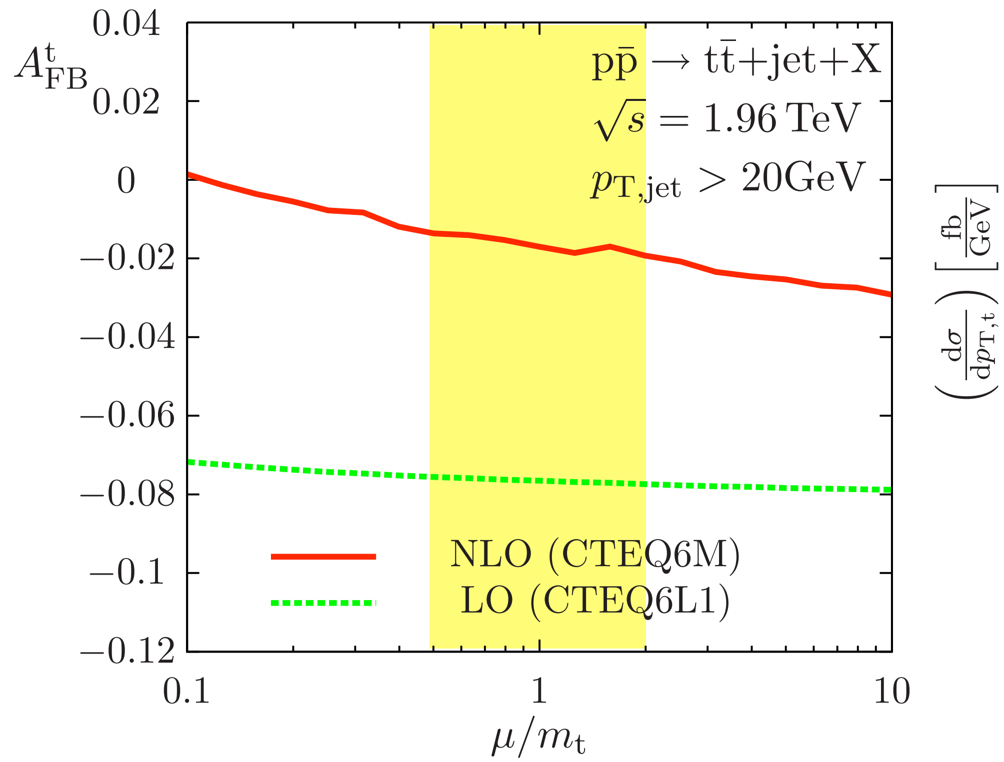


One NLO example: tt +1 jet

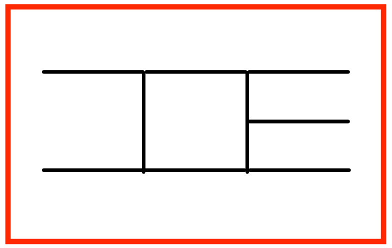
Calculation done with traditional methods

Dittmaier, Kallweit, Uwer '07, '08

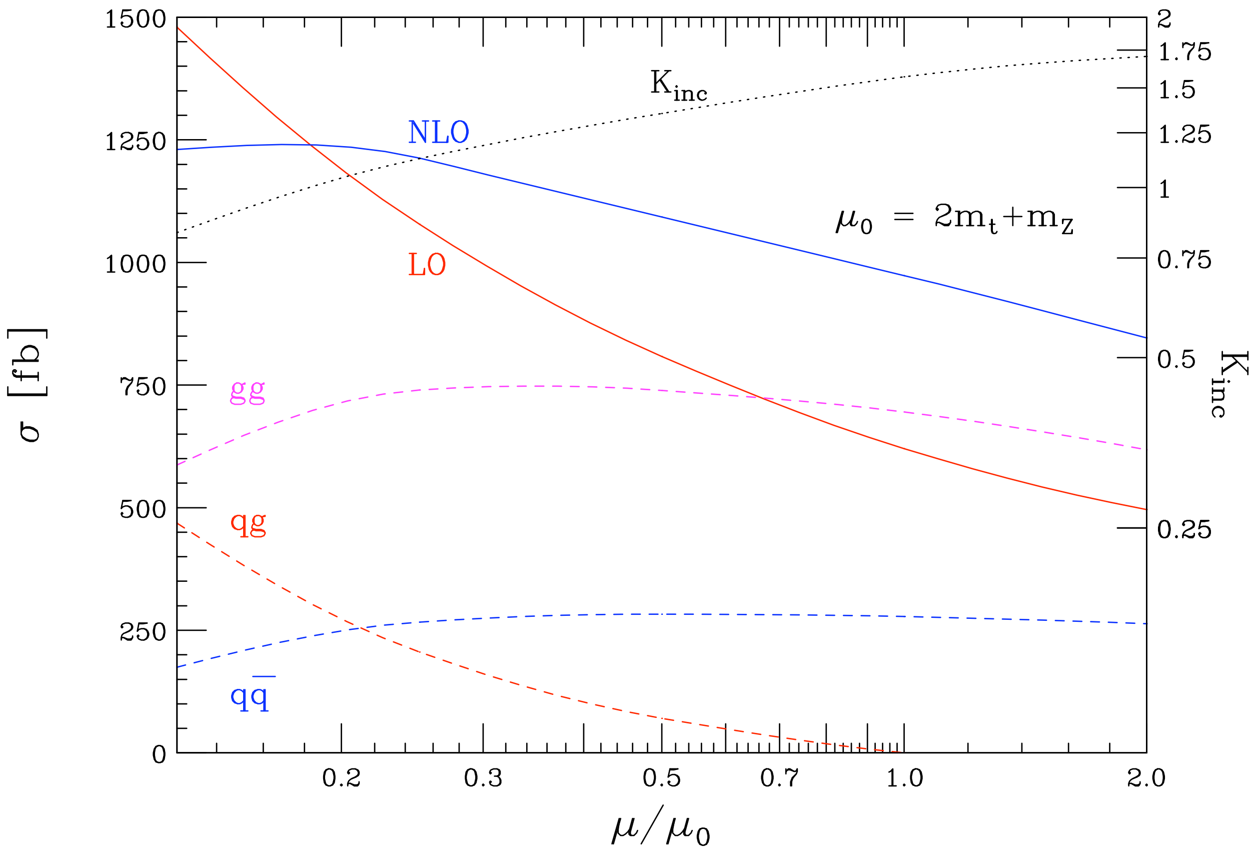


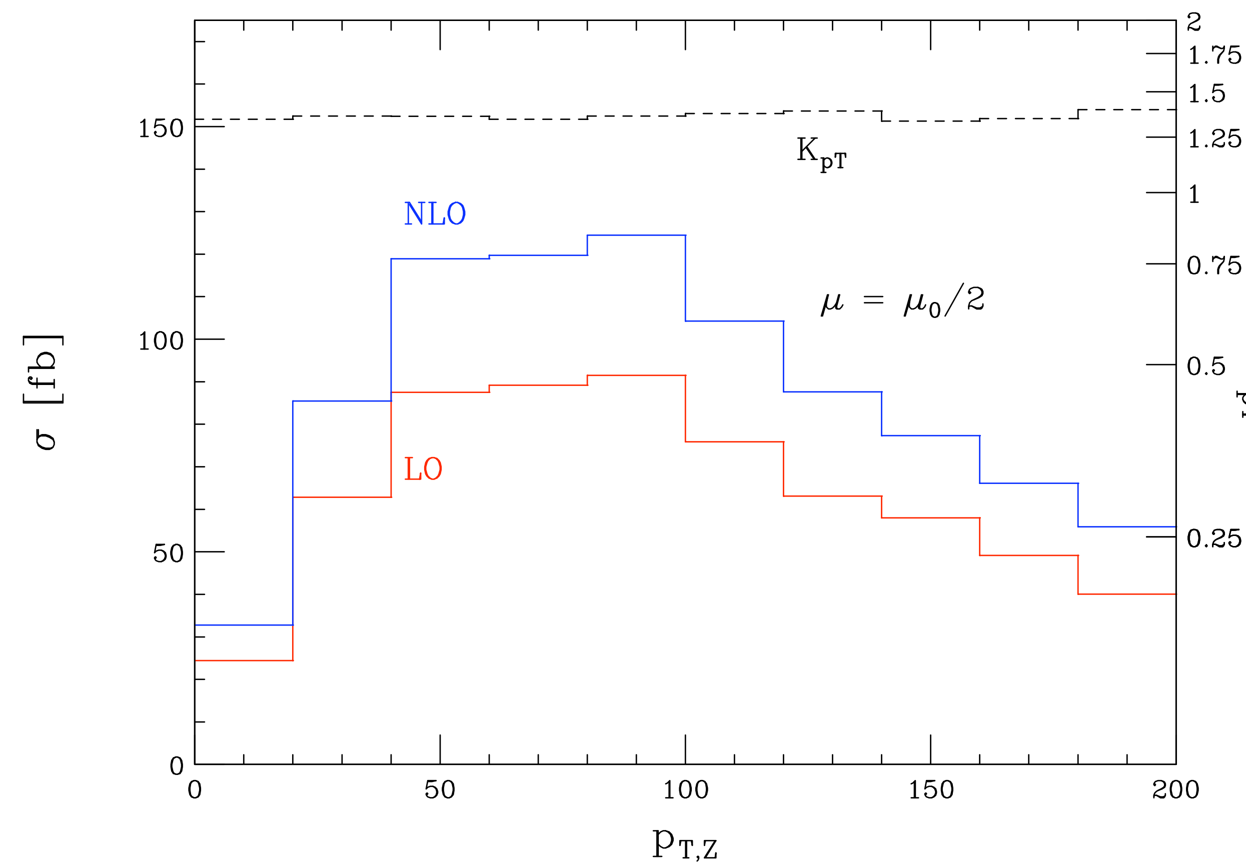


- improved stability of NLO result [differential, but no decays]
- large effect on A_{FB} at the Tevatron: now compatible with zero
- essential ingredient of NNLO tt production



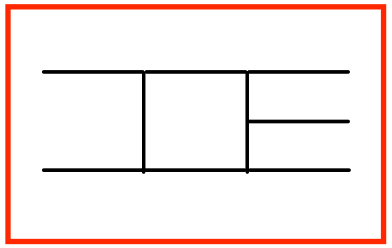
2nd NLO example: tt +Z





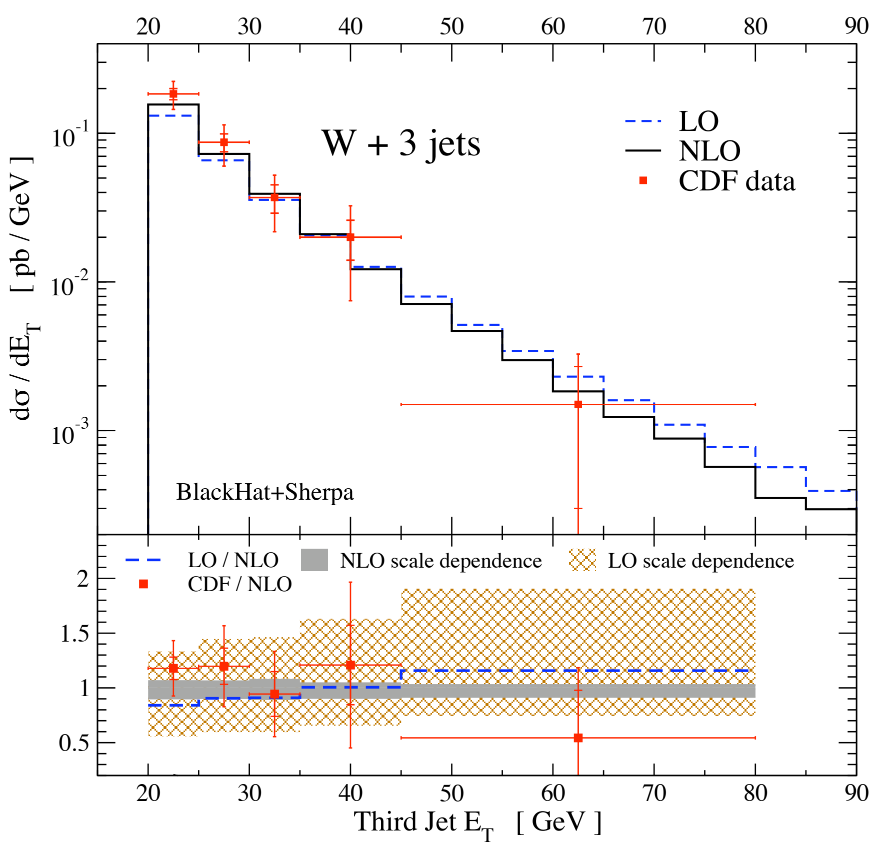
Lazopoulos, Melnikov, Petriello '08

- NLO increase cross section by 35% (residual 10% uncertainty)
- factor of 1.5-2 improvement on ttZ measurement (probe BSM)
- no significant change in distributions



W + 3 jets

Measured at the Tevatron + of primary importance at the LHC: background to model- independent new physics searches using jets + MET

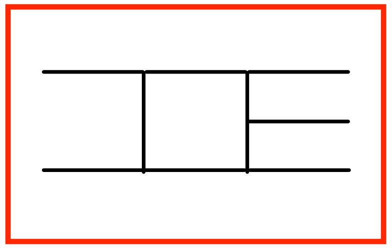


number of jets	CDF	LC NLO	NLO
1	53.5 ± 5.6	$58.3^{+4.6}_{-4.6}$	$57.8^{+4.4}_{-4.0}$
2	6.8 ± 1.1	$7.81^{+0.54}_{-0.91}$	$7.62^{+0.62}_{-0.86}$
3	0.84 ± 0.24	$0.908^{+0.044}_{-0.142}$	$0.882(5)^{+0.057}_{-0.138}$

Preliminary

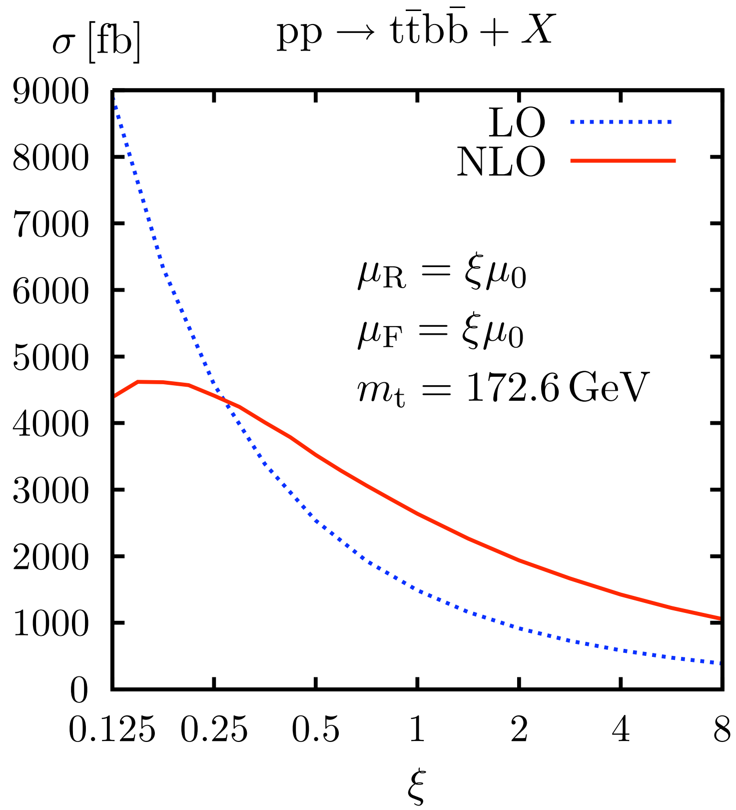
Berger et al. '09; also Ellis et al. '09 (LC)

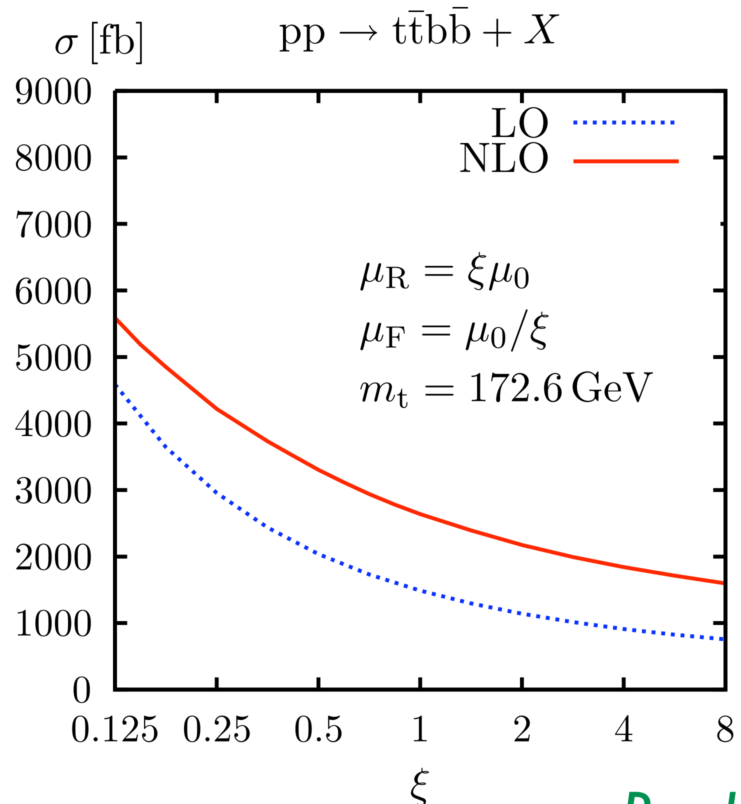
- ☺ Small K=1.0-1.1, reduced uncertainty: 50% (LO) → 10% (NLO)
- ☺ First applications of new techniques to 2 → 4 LHC processes



pp → tt bb

Measurement of ttH impossible without knowledge of pp → tt bb at NLO (need also pp → tt jj) + interesting per se



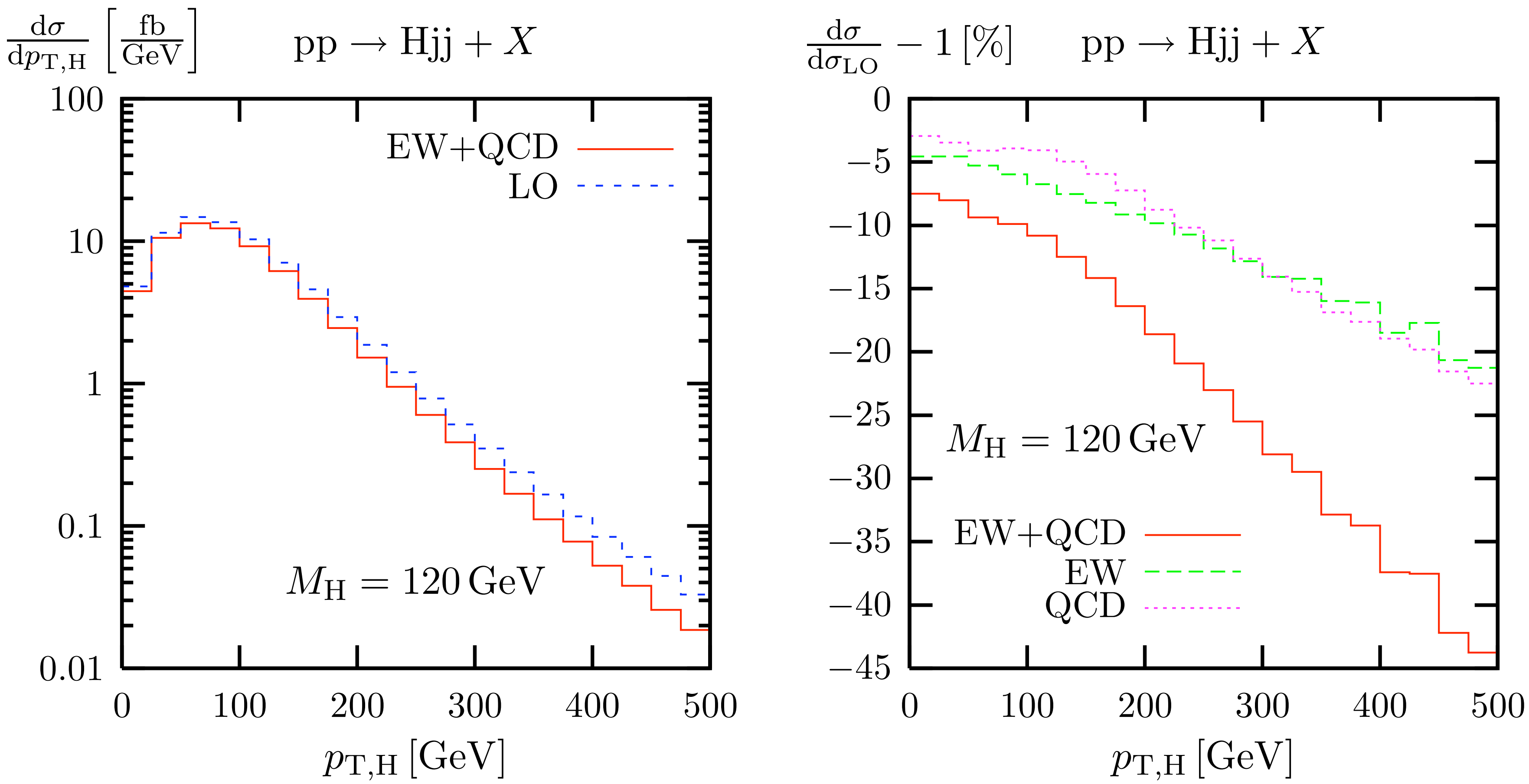


Bredenstein et al. '09

- ☹ Large K=1.8, large residual uncertainties: 70% (LO) → 35% (NLO)
- ☺ Demonstrates feasibility of Feynman diagrams calculation for $2 \to 4$ LHC processes

The “not so weak” EW :VBF Higgs

Ciccolini, Denner, Dittmaier ’07



EW and QCD of the same size

☛ importance of EW corrections for precision studies (peaks) and in tails of distributions (large electro-weak logarithms)

General NLO features?

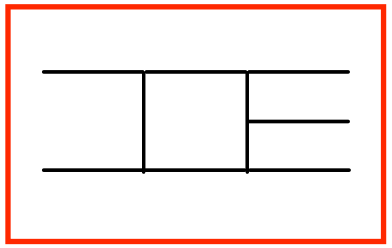
Process	Typical scales μ_0	μ_1	Tevatron K-factor $\mathcal{K}(\mu_0)$	$\mathcal{K}(\mu_1)$	$\mathcal{K}'(\mu_0)$	LHC K-factor $\mathcal{K}(\mu_0)$	$\mathcal{K}(\mu_1)$	$\mathcal{K}'(\mu_0)$
W	m_W	$2m_W$	1.33	1.31	1.21	1.15	1.05	1.15
W+1jet	m_W	p_T^{jet}	1.42	1.20	1.43	1.21	1.32	1.42
W+2jets	m_W	p_T^{jet}	1.16	0.91	1.29	0.89	0.88	1.10
WW+jet	m_W	$2m_W$	1.19	1.37	1.26	1.33	1.40	1.42
$t\bar{t}$	m_t	$2m_t$	1.08	1.31	1.24	1.40	1.59	1.48
$t\bar{t}$+1jet	m_t	$2m_t$	1.13	1.43	1.37	0.97	1.29	1.10
$b\bar{b}$	m_b	$2m_b$	1.20	1.21	2.10	0.98	0.84	2.51
Higgs	m_H	p_T^{jet}	2.33	–	2.33	1.72	–	2.32
Higgs via VBF	m_H	p_T^{jet}	1.07	0.97	1.07	1.23	1.34	1.09
Higgs+1jet	m_H	p_T^{jet}	2.02	–	2.13	1.47	–	1.90
Higgs+2jets	m_H	p_T^{jet}	–	–	–	1.15	–	–

NLO report '08

<u>General features:</u>

- color annihilation, gluon dominated ⇒ large K-factors
- extra legs in the final state ⇒ smaller K-factors

But be careful, only full calculations can really tell!



NLO + parton shower

Combine best features:

Get correct rates (NLO) and hadron-level description of events (PS)

Difficult because need to avoid double counting at NLO

Working LHC examples:

- MC@NLO

  add difference between exact NLO and (MC) NLO
  - W/Z
  - WW, WZ, ZZ
  - Higgs
  - heavy quark
  - single-top (also with W)
  - Higgs + V

  Frixione & Webber '02 and later refs.

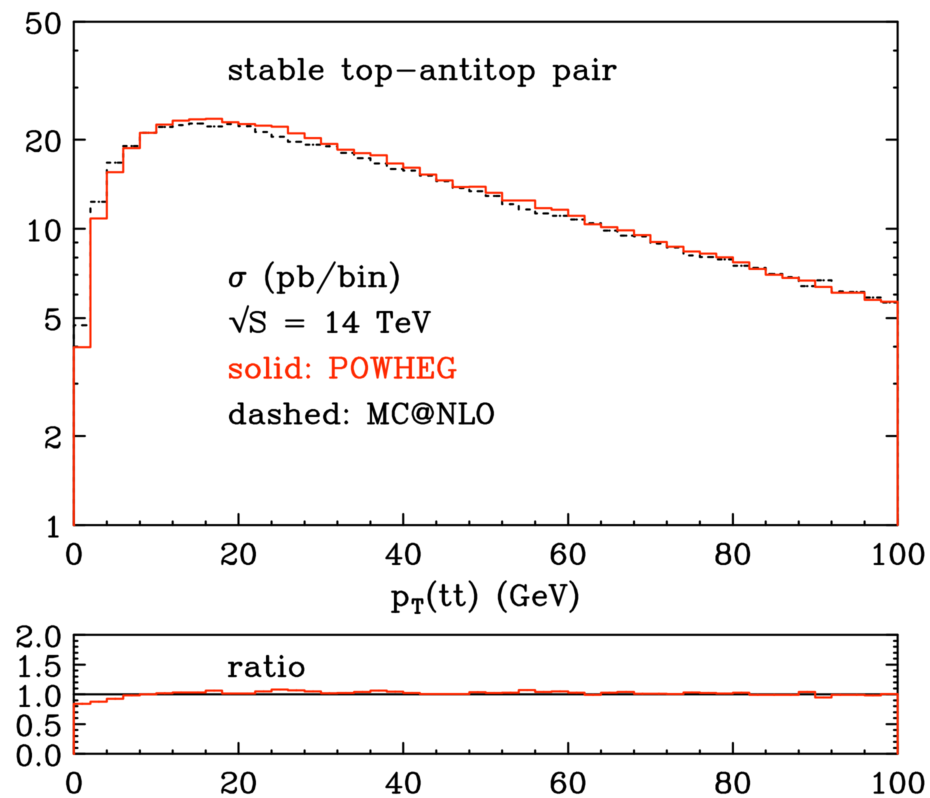
- POWHEG

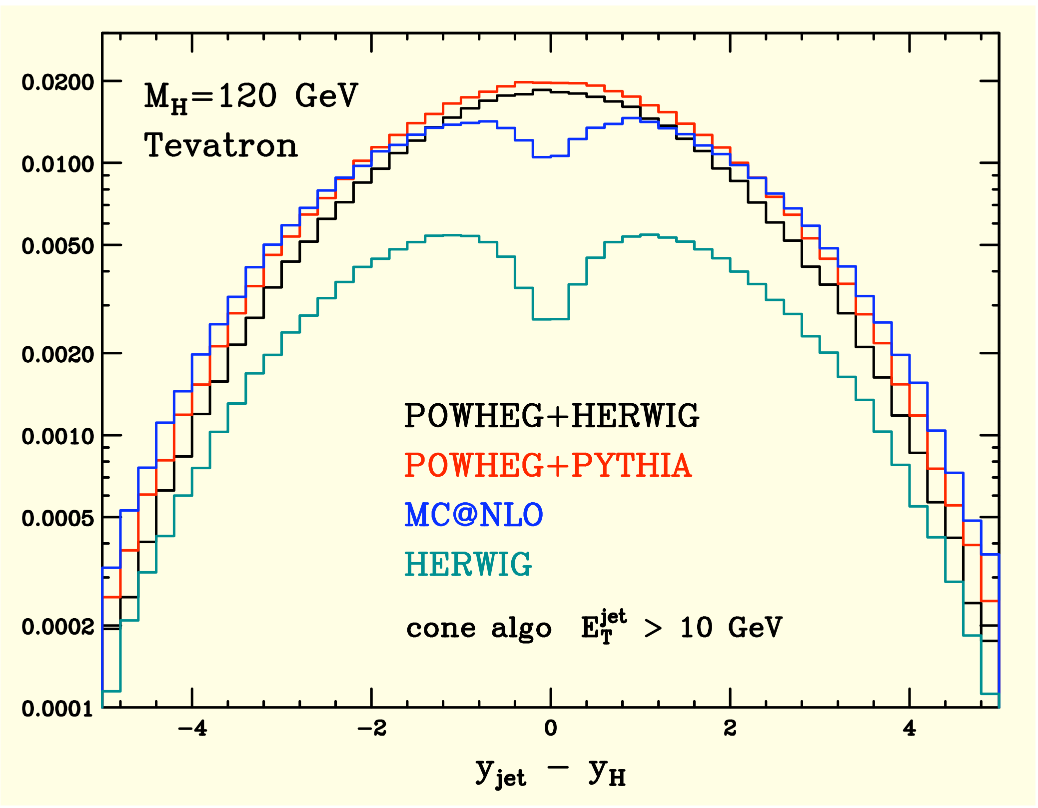
  generated the hardest emission 1st, then shower independently
  - ZZ
  - heavy quark
  - W/Z
  - Higgs, Higgs + V
  - single top
  - Z + jet (preliminary)

  Nason '04 and later refs.

MC@NLO vs. PowHeg

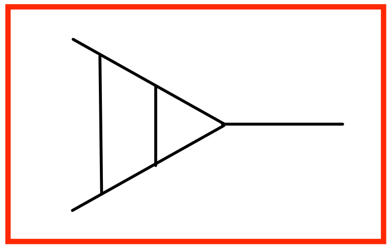
Examples:





⇒ agreement for many processes/observables considered (difference = different treatment of higher order terms, but sometimes important)

⇒ importance of independent calculations



When is NLO not good enough?

- when NLO corrections are large (NLO correction ≈ LO)
  This may happen when
  - process involves very different scales → large logarithms
  - new channels open up (at NLO they are effectively LO)
  - gluon dominated processes

- when high precision is useful (occasionally the case)
  - Drell-Yan, heavy-quark production, 3 jets in e^+e^-, ...

- when a reliable error estimate is wanted

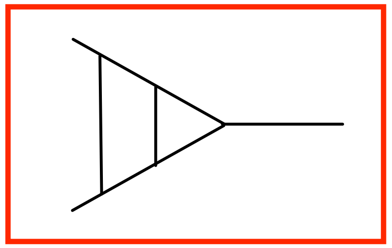
Collider processes known at NNLO

Collider processes known at NNLO today:

(a) Drell-Yan (Z,W)

(b) Higgs

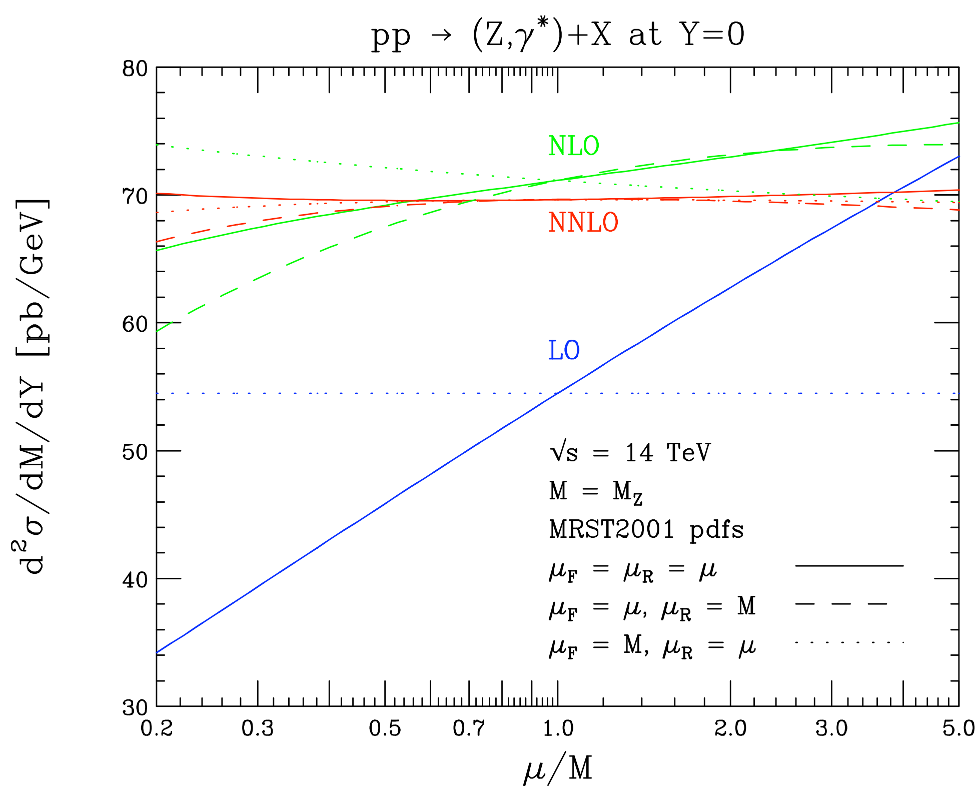
(c) 3-jets in e+e-

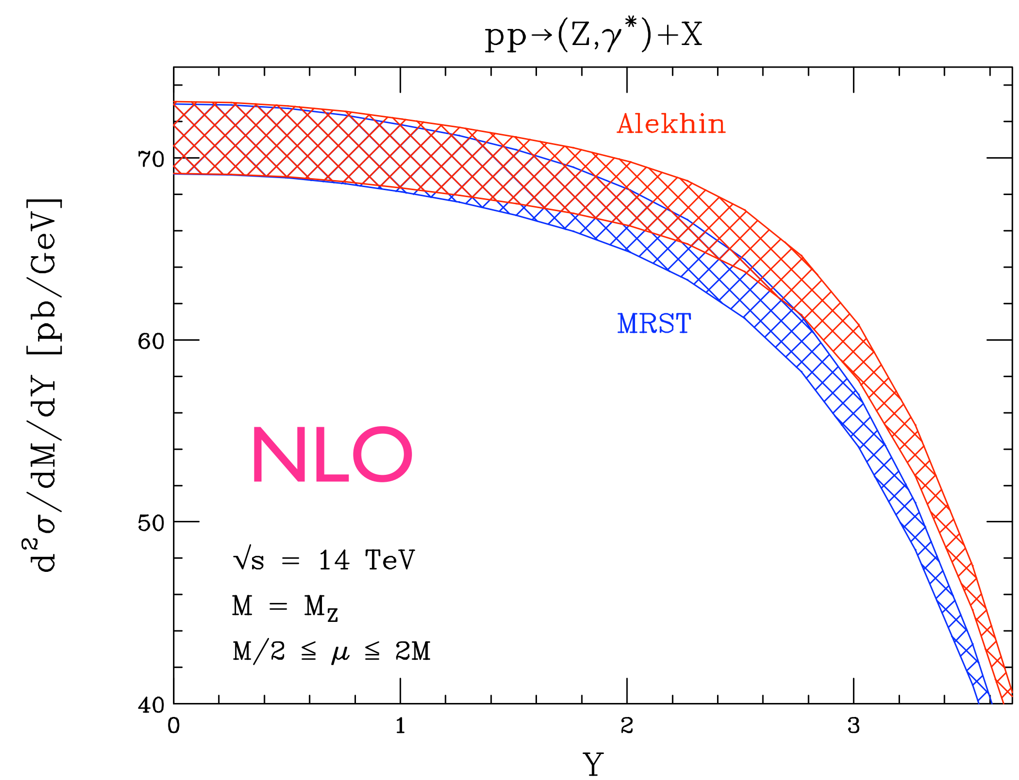


Drell-Yan

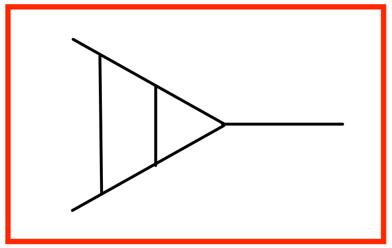
- most important and precise test of the SM at the LHC
- best known process at the LHC: spin-correlations, finite-width effects, γ-Z interference, fully differential in lepton momenta

<u>Scale stability and sensitivity to PDFs</u>





Anastasiou, Dixon, Melnikov, Petriello '03, '05; Melnikov, Petriello '06



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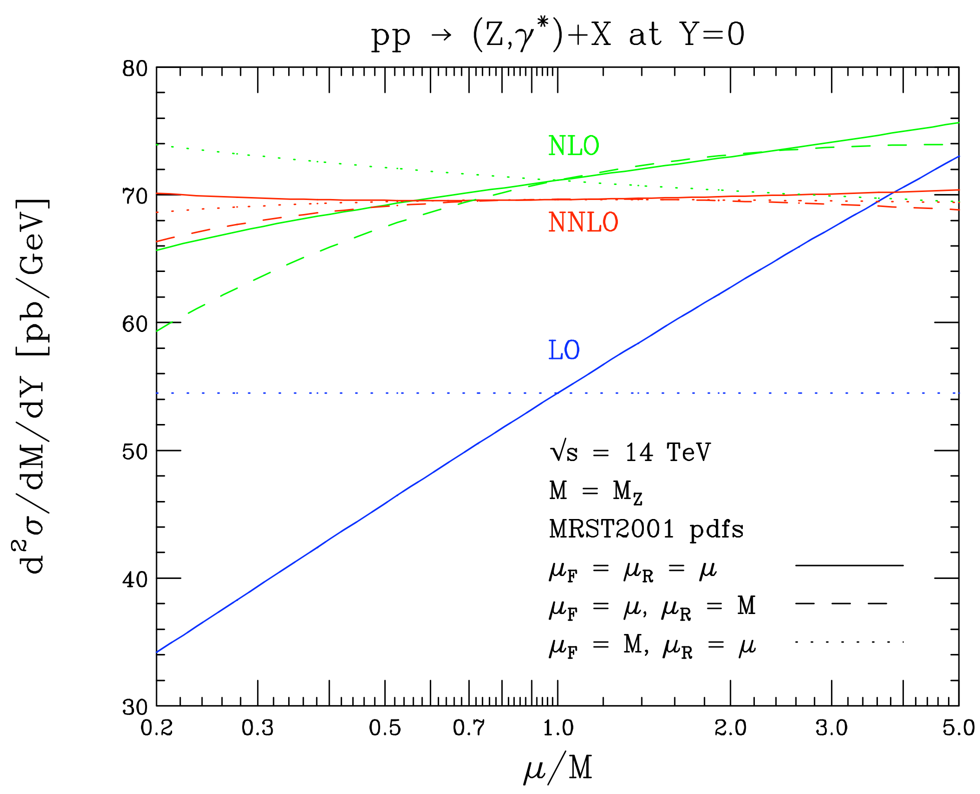
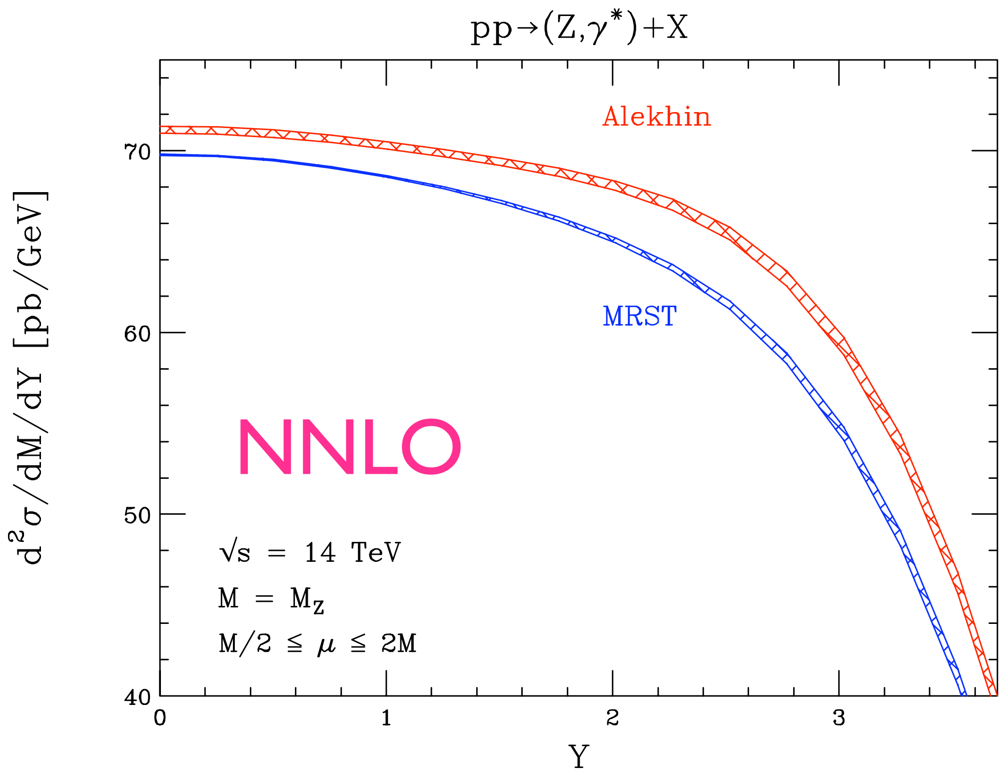
Scale stability and sensitivity to PDFs





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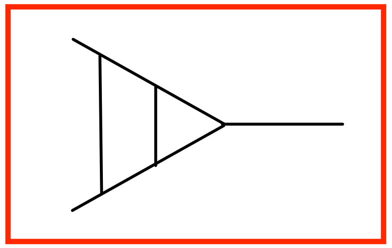
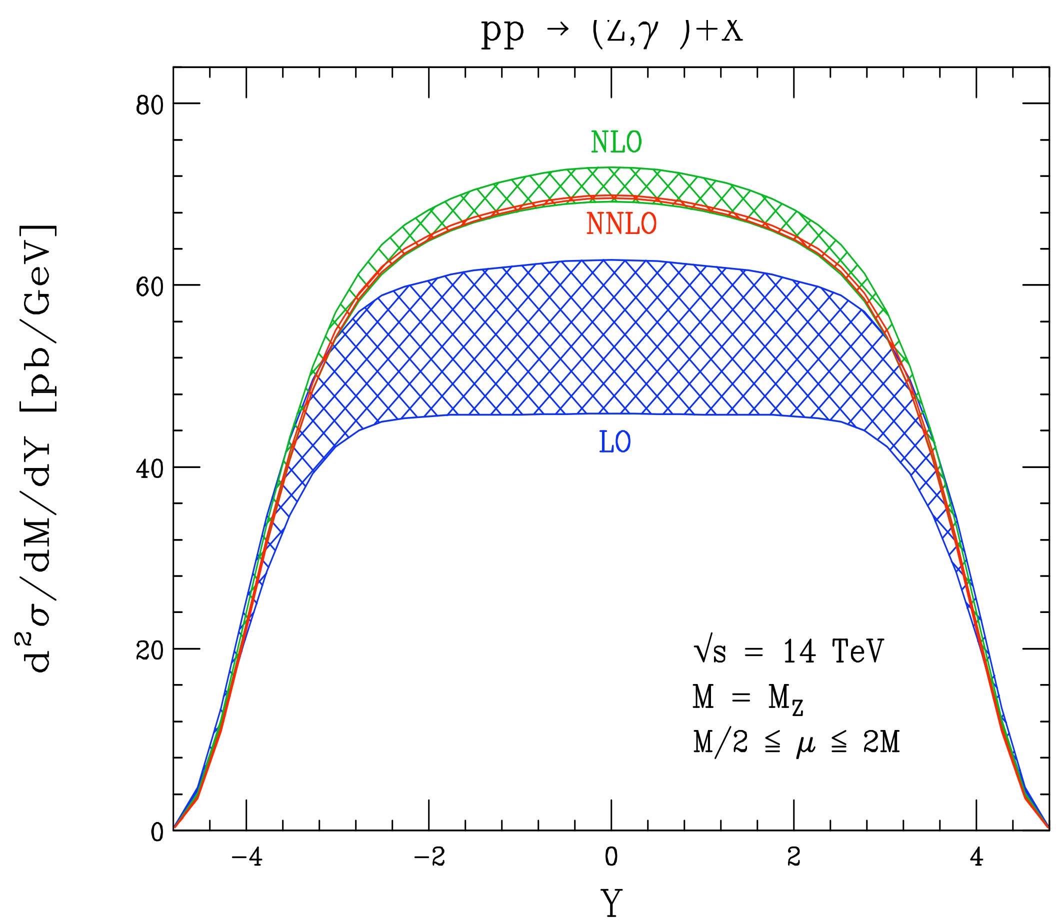
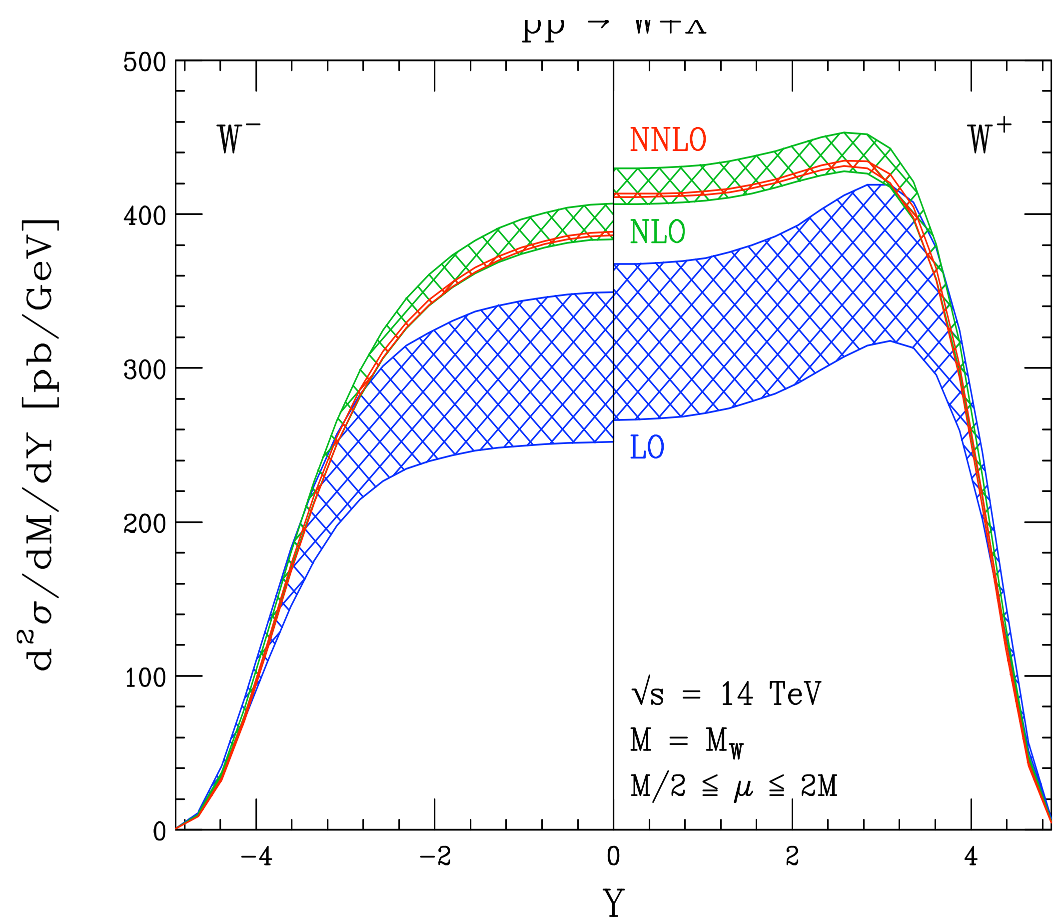


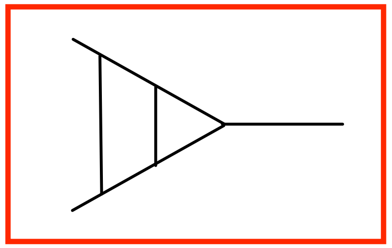
Drell-Yan: rapidity distributions





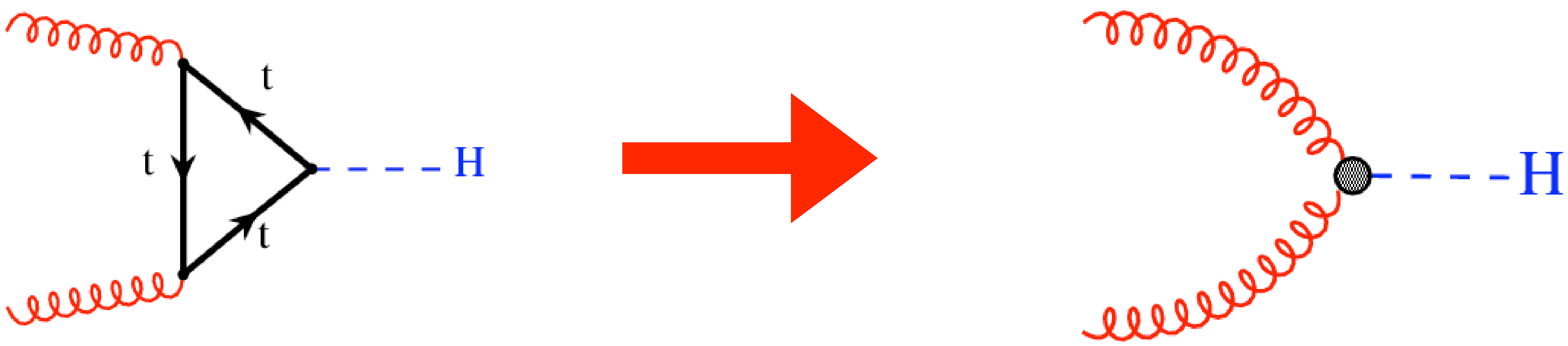
Anastasiou, Dixon, Melnikov, Petriello '03, '05; Melnikov, Petriello '06

☛ at the LHC: perturbative accuracy better than 1%

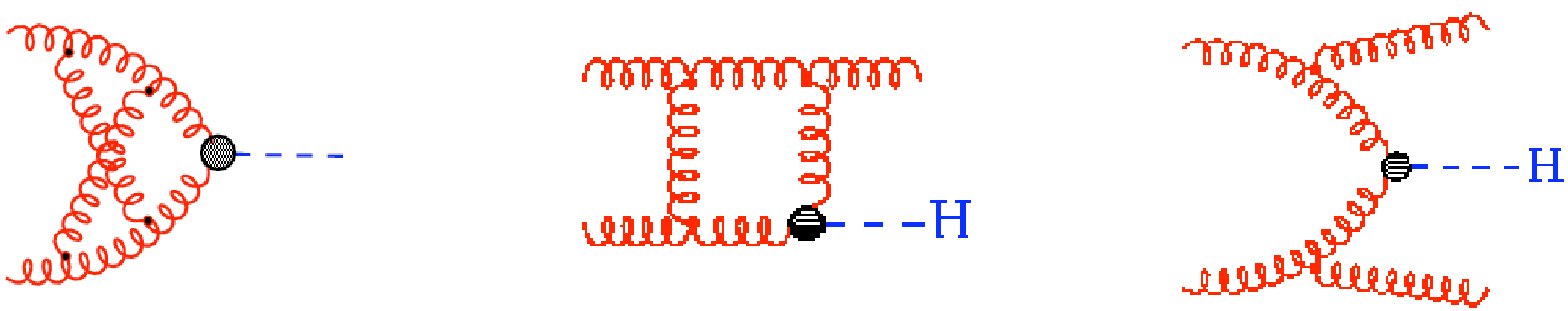


Inclusive NNLO Higgs production

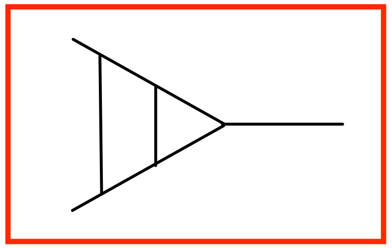
Inclusive Higgs production via gluon-gluon fusion in the large m_t-limit:



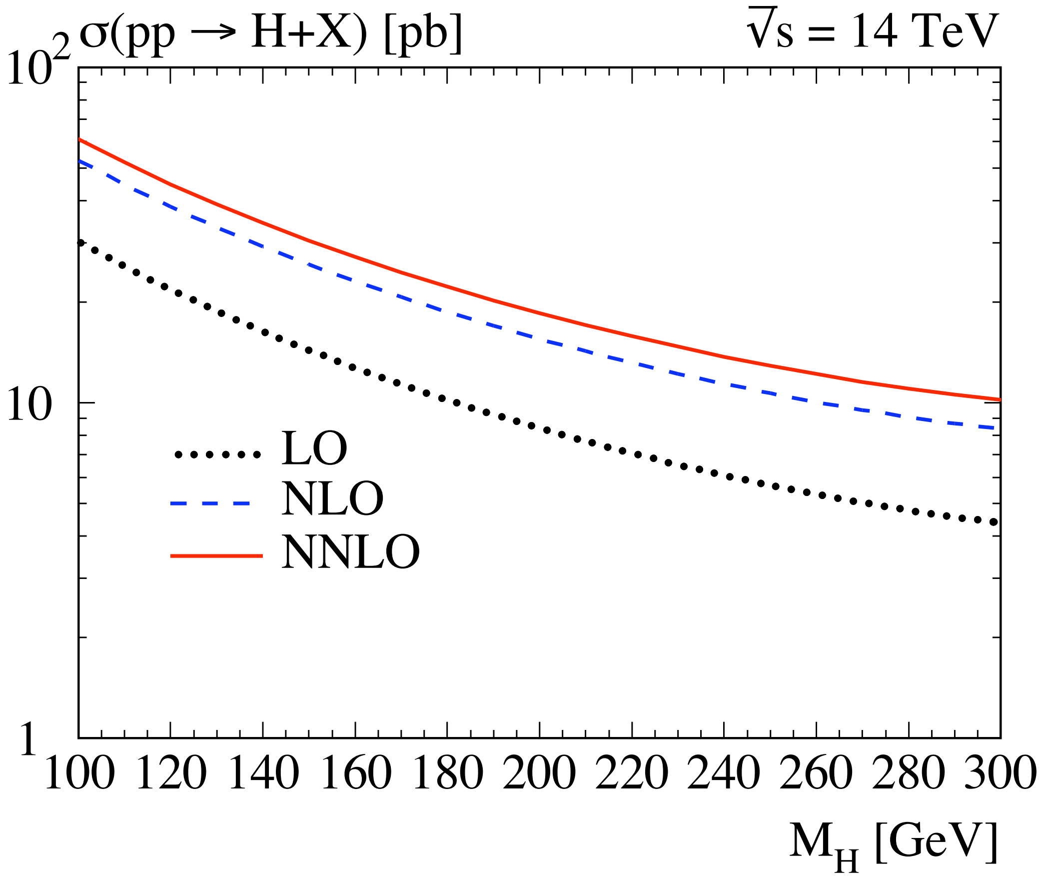
NNLO corrections knows since few years now:

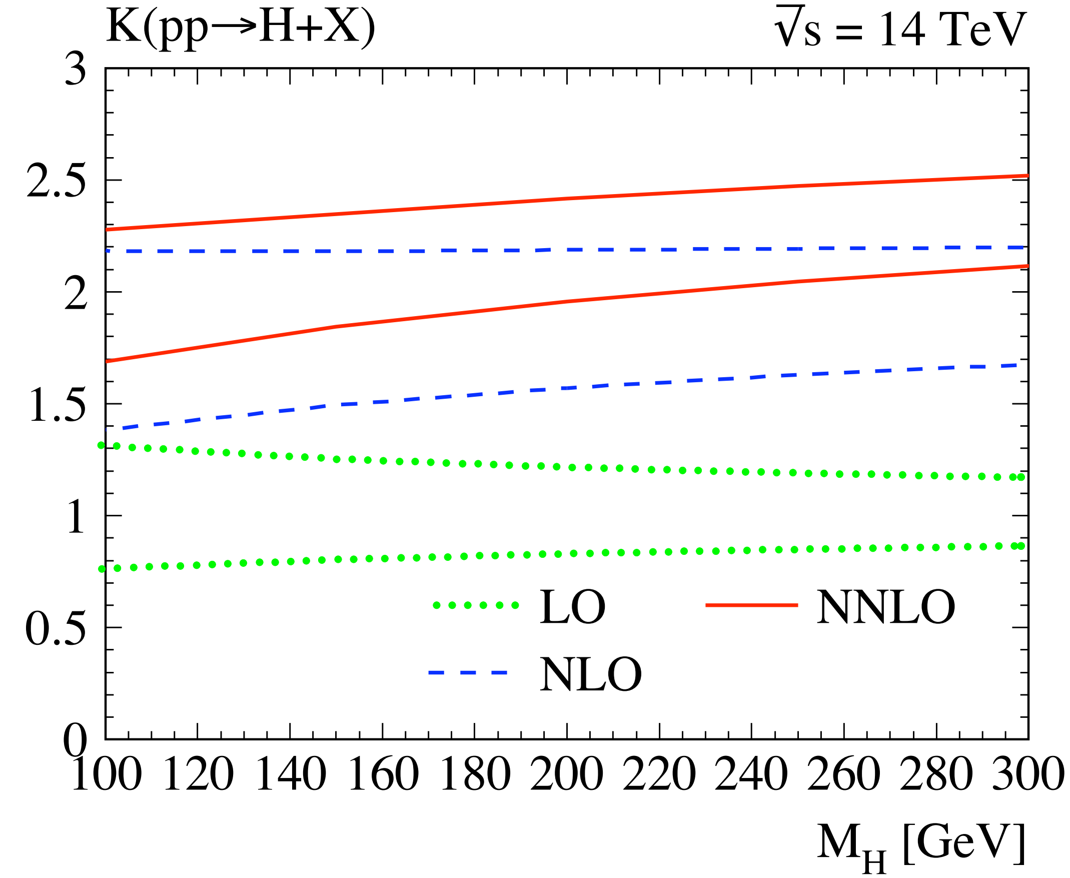


virtual-virtual real-virtual real-real



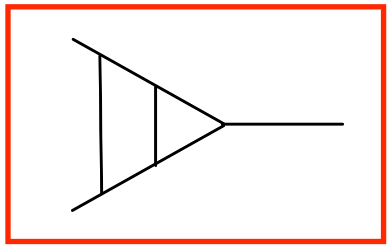
Inclusive NNLO Higgs production



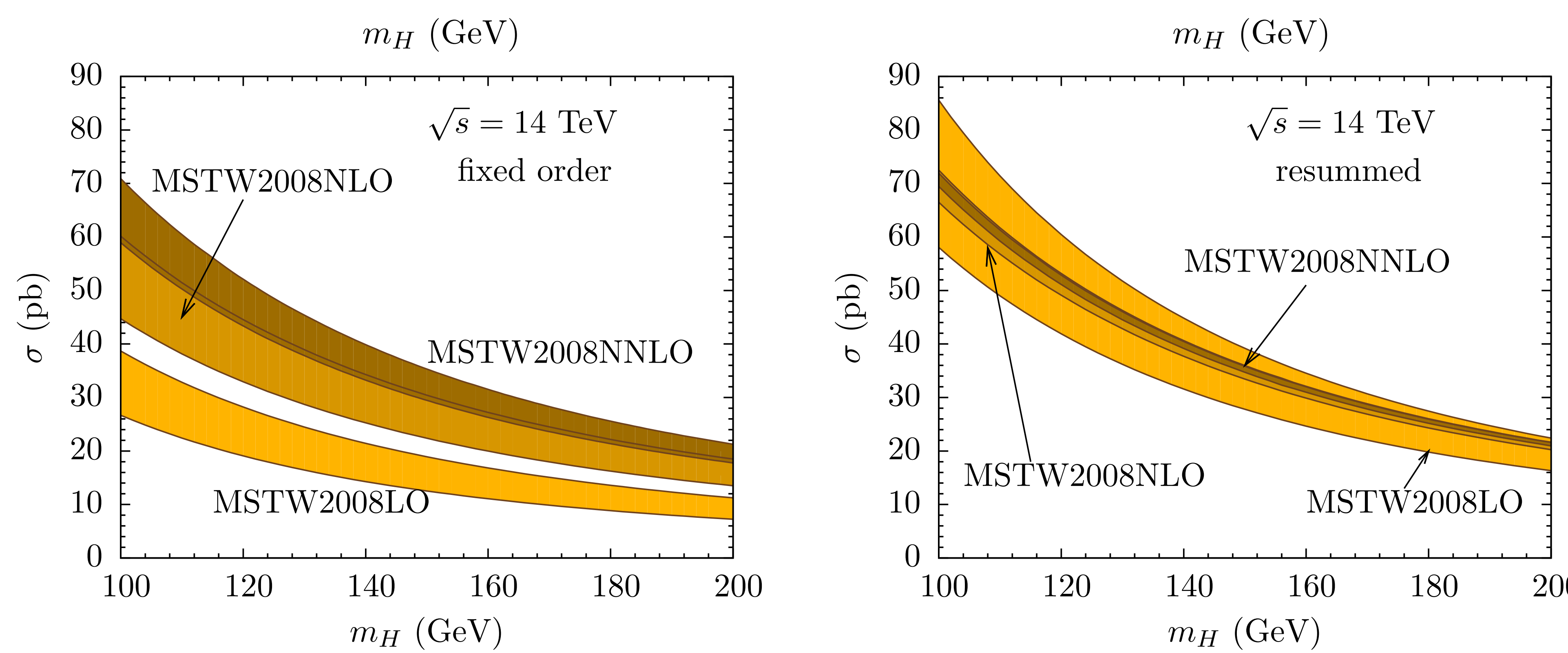


Kilgore, Harlander '02

Anastasiou, Melnikov '02

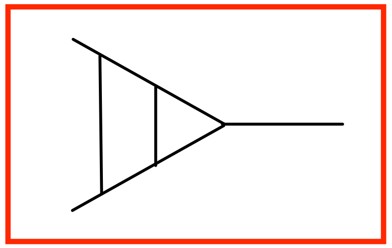


RGE improved Higgs production



Ahrens et al. '08

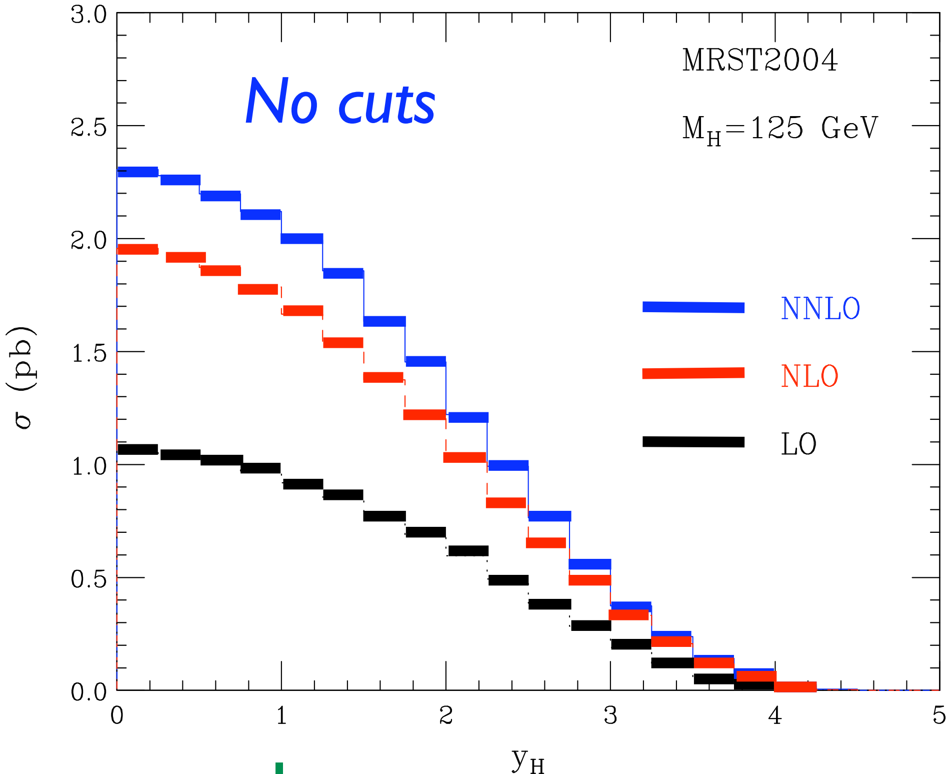
- ☛ improve convergence of PT expansion by matching effective theory in the space-like region ($\mu^2 < 0$) and do RGE to the time-like one ($\mu^2 > 0$)
- ☛ residual 8% (13%) effect at the LHC (Tevatron)

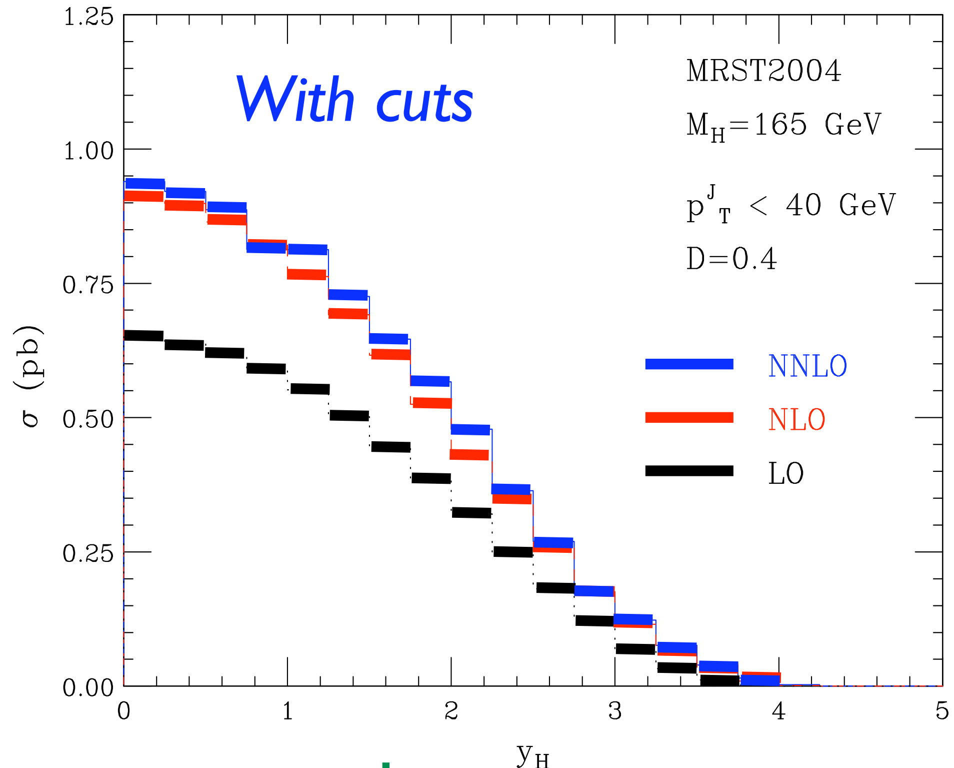


Exclusive NNLO Higgs production

First fully exclusive $H \to WW \to 2l\, 2\nu$ NNLO calculation

Anastasiou, Dissertori, Stoeckli '07; also Catani, Grazzini '08



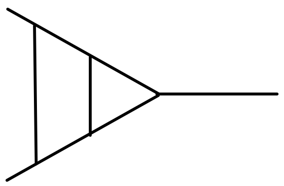


☛ slow convergence

☛ good convergence

⇒ impact of NNLO dramatically reduced by cuts

Very important to include cuts and decays in realistic studies



NNLO 3-jets in e^+e^-

Motivation: error on α_s from jet-observables

$$\alpha_s(M_Z) = 0.121 \pm 0.001\,(\text{exp.}) \pm 0.005\,(\text{th.})$$

Bethke '06

➡ dominated by theoretical uncertainty

NNLO 3-jet calculation in e^+e^- completed in 2007

Method: developed antenna subtraction at NNLO

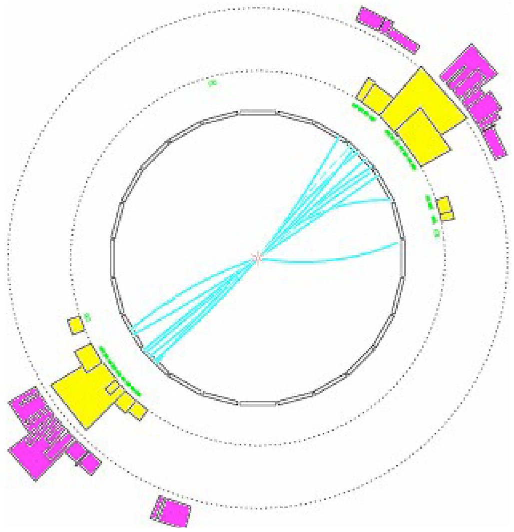
First application: NNLO fit of α_s from event-shapes

Event shapes

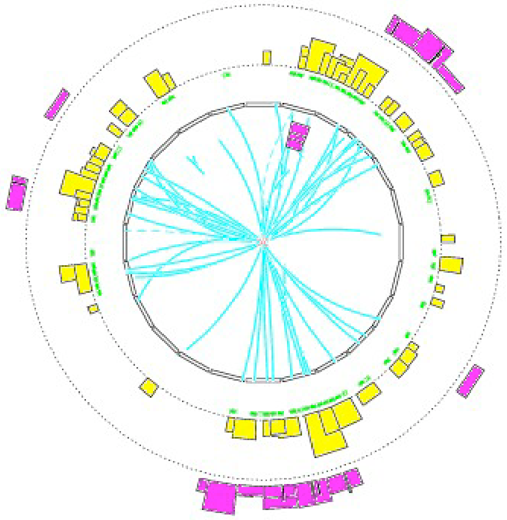
Event-shapes and jet-rates: infrared safe observables describing the energy and momentum flow of the final state.

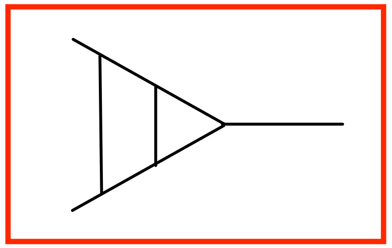
Candle example in e^+e^-: The thrust $$T = \max_{\vec{n}} \frac{\sum_i \vec{p}_i \cdot \vec{n}}{\sum_i |\vec{p}_i|}$$

Pencil-like event: $1 - T \ll 1$



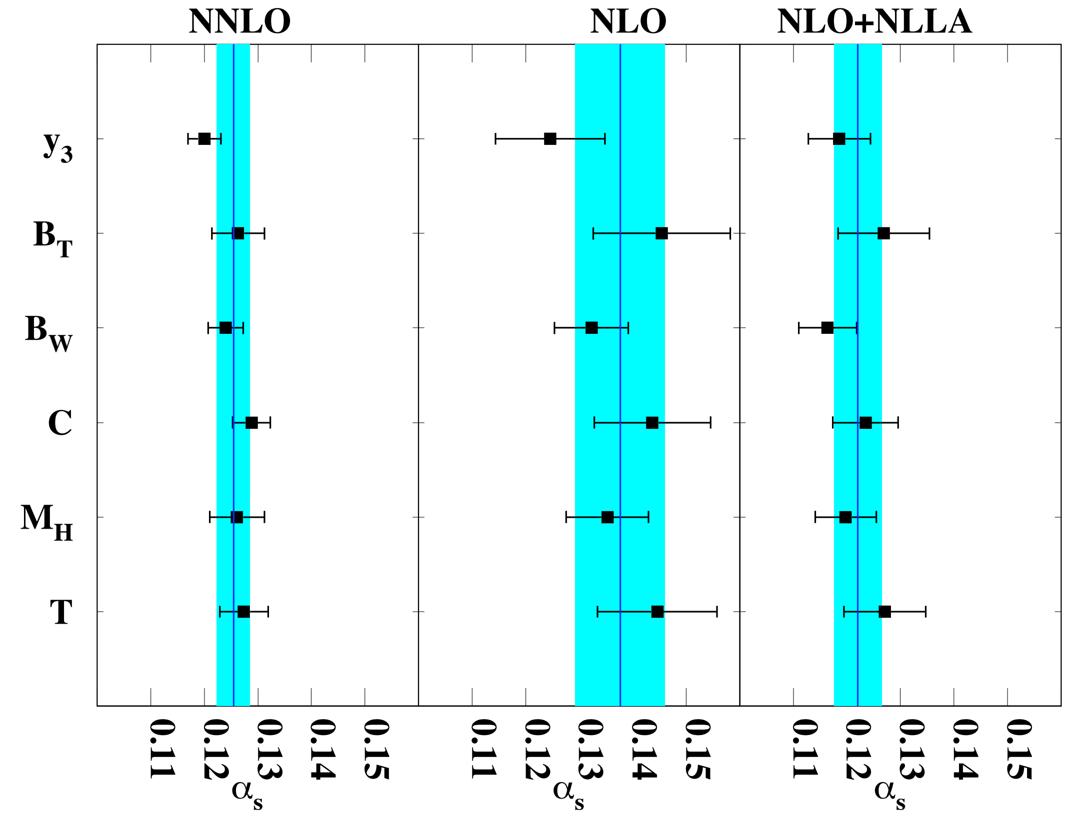
Planar event: $1 - T \sim 1$





α_s from event shapes at NNLO

- scale variation reduced by a factor 2
- scatter between α_s from different event-shapes reduced
- better χ^2, central value closer to world average
- study of moments of event-shapes

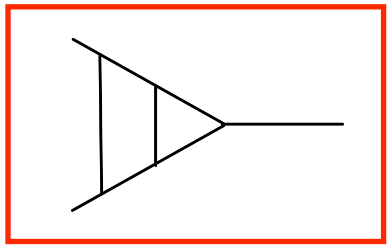


$$\alpha_s(M_Z^2) = 0.1240 \pm 0.0008\,(\mathrm{stat}) \pm 0.0010\,(\mathrm{exp}) \pm 0.0011\,(\mathrm{had}) \pm 0.0029\,(\mathrm{theo})$$

Dissertori et al. '07; Gehrmann et al. '08 - '09

Subsequent calculations identified a problem in 2 color structures in 2-jet region, now fixed

Becher et al. '08; Weinzierl '08



NNLO on the horizon

Single-jet production

- needed to constrain gluon PDF and coupling constant
- matrix elements known for some time
- subtraction in progress

Anastasiou et al.; Bern et al.; Daleo et al.

Top pair production

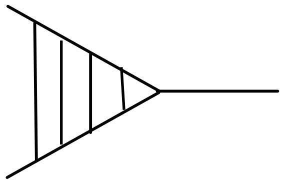
- needed for more precise m_t determination
- possibly for further constraining PDFs
- matrix elements partially known

Czakon et al.; Bonciani et al.; Kiyo et al.

Vector boson pair production

- study gauge structure of SM (triple gauge couplings)
- irreducible background for Higgs search in intermediate mass region
- NLO corrections are large

Chachamis, Czakon, Eiras



All order formula for IR divergences

Anomalous dimension:

$$\mathbf{\Gamma} = \sum_{(i,j)} \mathbf{T}_i \cdot \mathbf{T_j}\, \Gamma_{\rm cusp}(\alpha_s) \ln \frac{\mu^2}{-s_{ij}} + \sum_i \gamma^i(\alpha_s)$$

Becher, Neubert '09

See also: Dixon, Sterman, Aybat '08; Gardi & Magnea '09; Dixon '09 & refs. therein

☛ only color-dipole correlations

Singularities cancel in physical quantities, but important for

- ☛ Sudakov resummation
- ☛ check of virtual results
- ☛ insight into the structure of gauge theories

Extension to the massive partons more complicated

Mitov, Sterman, Sung '09; Becher, Neubert '09

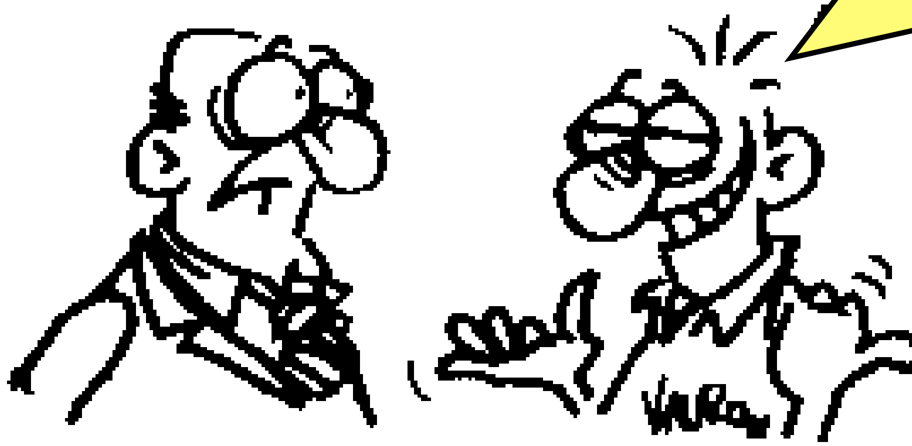
Jets: few years ago

Cones are IR unsafe!

The Cone is too rigid!

IR unsafety affects jet cross-sections by less than 1%, so don't need to care!

kt collects too much soft radiation!



Cones have a well-defined circular area!

Jet area not well defined in kt: U.E. and pile-up subtraction too difficult!

What about dark towers??

After all, if D=1.35 R Cone and kt are practically the same thing ...

Jet-algorithms

Cone type
(UA1, JetCLU, Midpoint, SISCone..)

☛ top down approach:
cluster particles according to distance in coordinate-space
Idea: put cones along dominant direction of energy flow

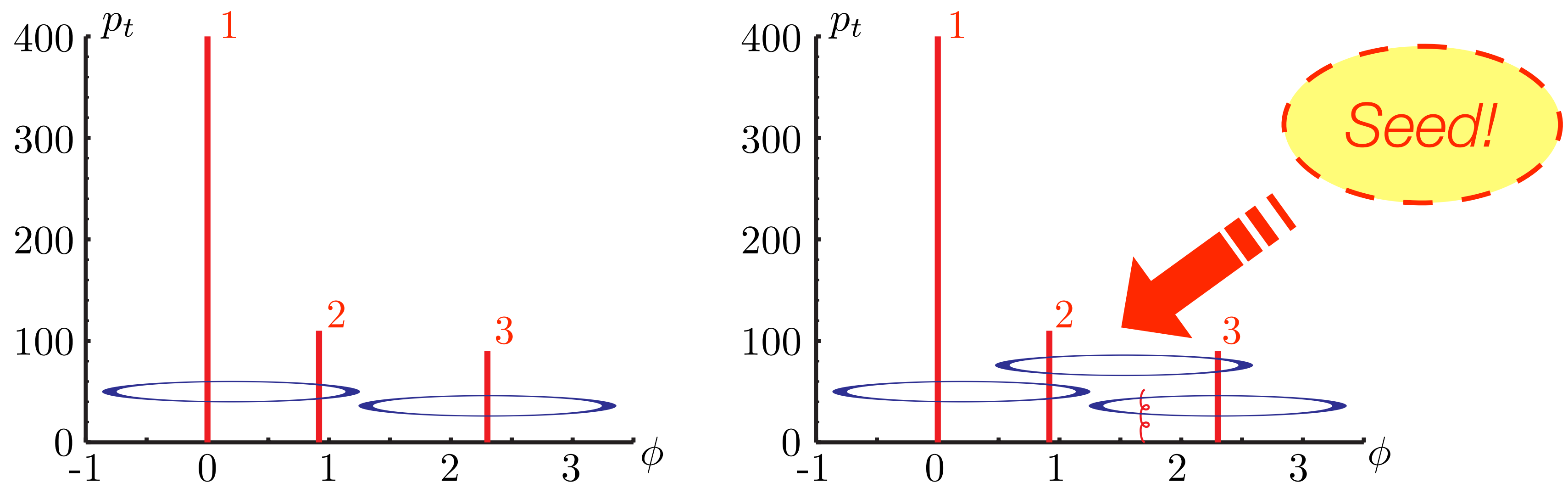
- ☺ intuitive, meant to be simple
- ☻ problems with IR-safety
- ☺ SIScone: IR-safe and fast

Sequential
(kt-type, Jade, Cambridge/Aachen...)

☛ bottom up approach:
particles according to distance in momentum-space
Idea: undo branchings occurred in the PT evolution

- ☺ simple, clean, IR-safe
- ☻ irregular, wide-reaching jets
- ☺ solved by anti-kt

Jets: IR-unsafety of midpoint



3 hard ⇒ 2 stable cones 3 hard + 1 soft ⇒ 3 stable cones

Soft emission changes the hard jets ⇒ algorithm is IR unsafe

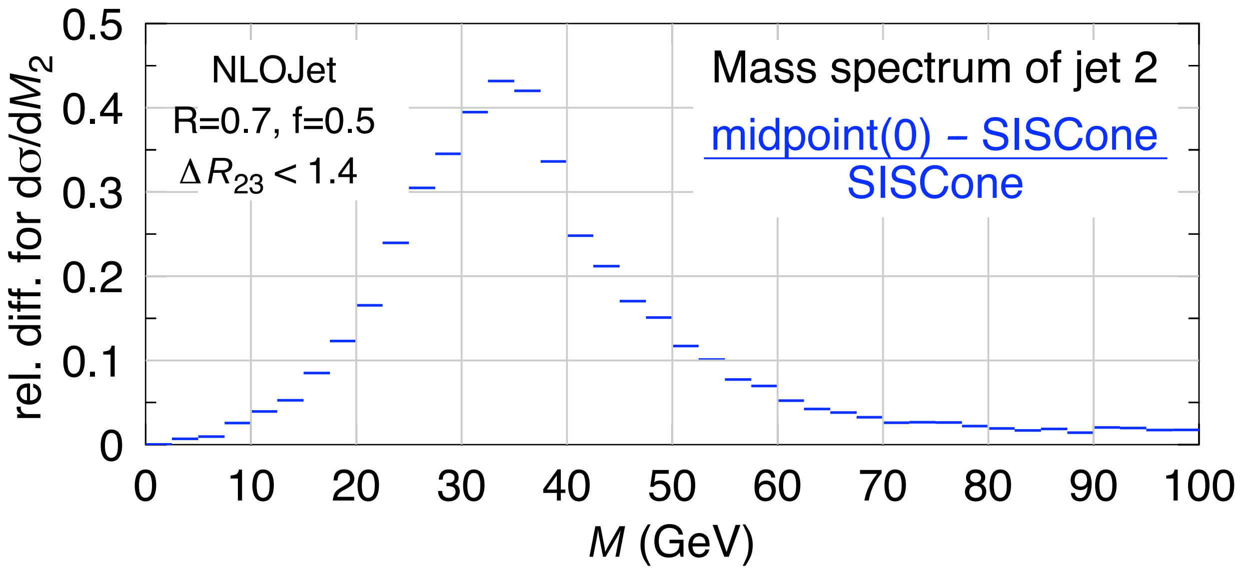
Solution: use a seedless algorithm find all stable cones [⇒ jets]

SISCone: complexity $N^2\log(N)$ *Salam, Soyez '07*

Similarly: iterative cone is collinear unsafe

Solution: anti-kt algorithm *Cacciari, Salam, Soyez '08*

Physical impact of IR-unsafety



Up to 40% difference in mass spectrum

IR-unsafety is an issue at the LHC

Observable	1st miss cones at	Last meaningful order
Inclusive jet cross section	NNLO	NLO
3 jet cross section	NLO	LO (NLO in NLOJet)
$W/Z/H$ + 2 jet cross sect.	NLO	LO (NLO in MCFM)
jet masses in 3 jets	LO	none (LO in NLOJet)

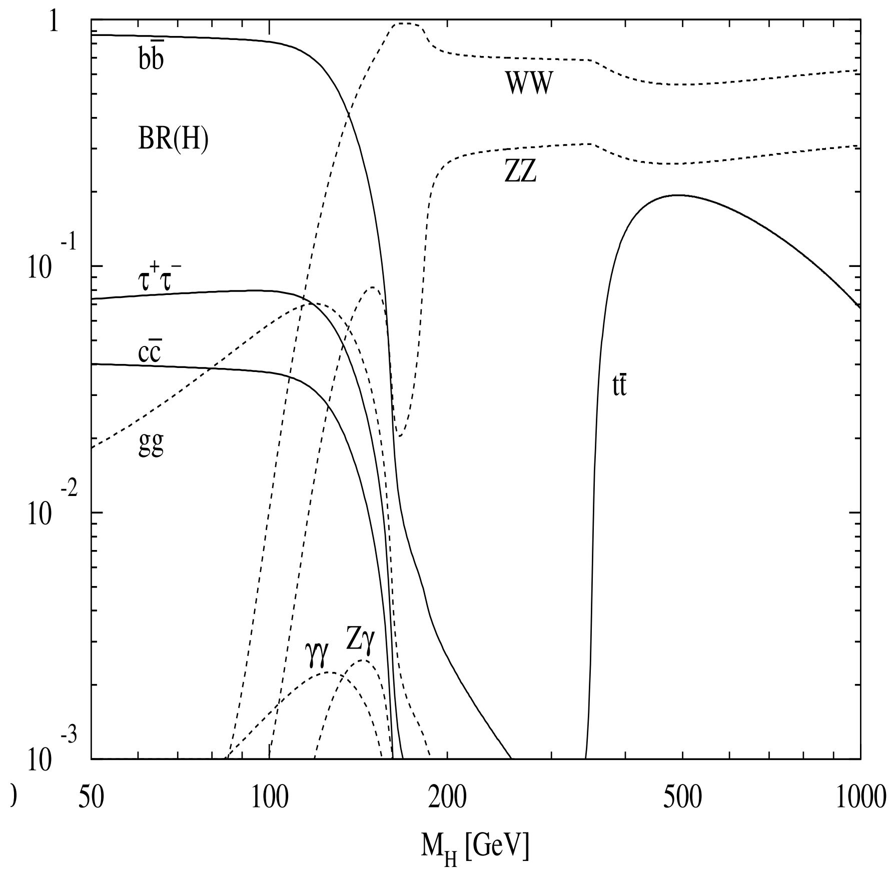
~~JetClu~~
~~ATLAS Cone~~
~~MidPoint~~
~~Iterative Cone~~

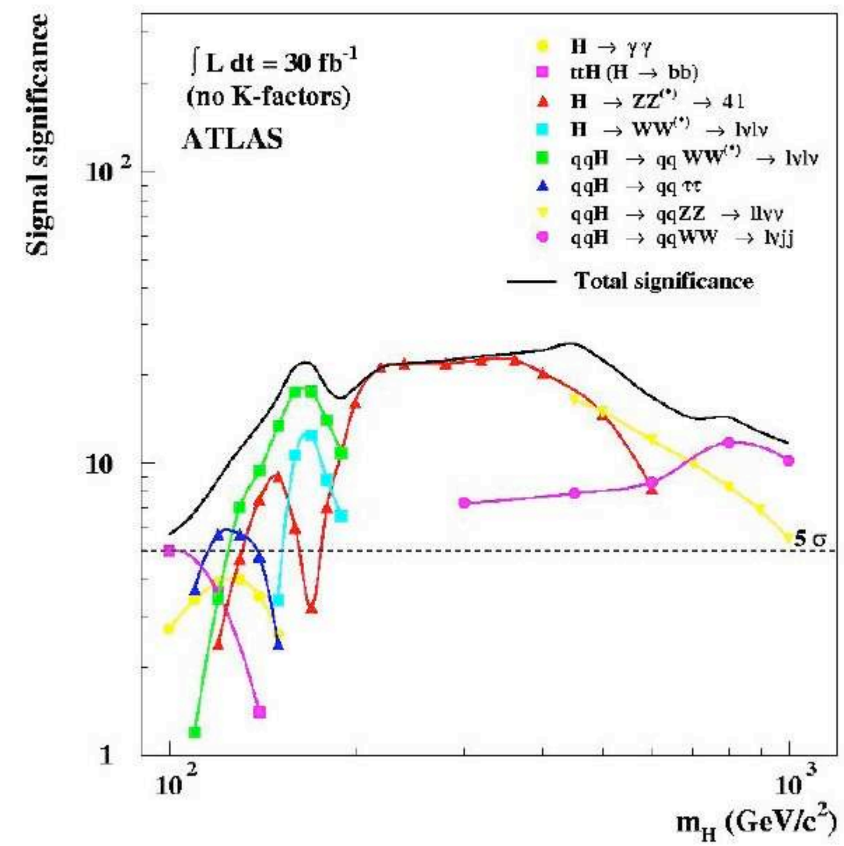
JetClu, ATLAS Cone, MidPoint → SISCone: ✓ as fast ✓ IRC safe

Iterative Cone → Anti-k_t: ✓ regular ✓ IRC safe

If you don't want theoretical efforts to be wasted!

Z/W+ H (→bb) rescued ?





⇒ Light Higgs hard: H→bb dominant, but overwhelmed by background

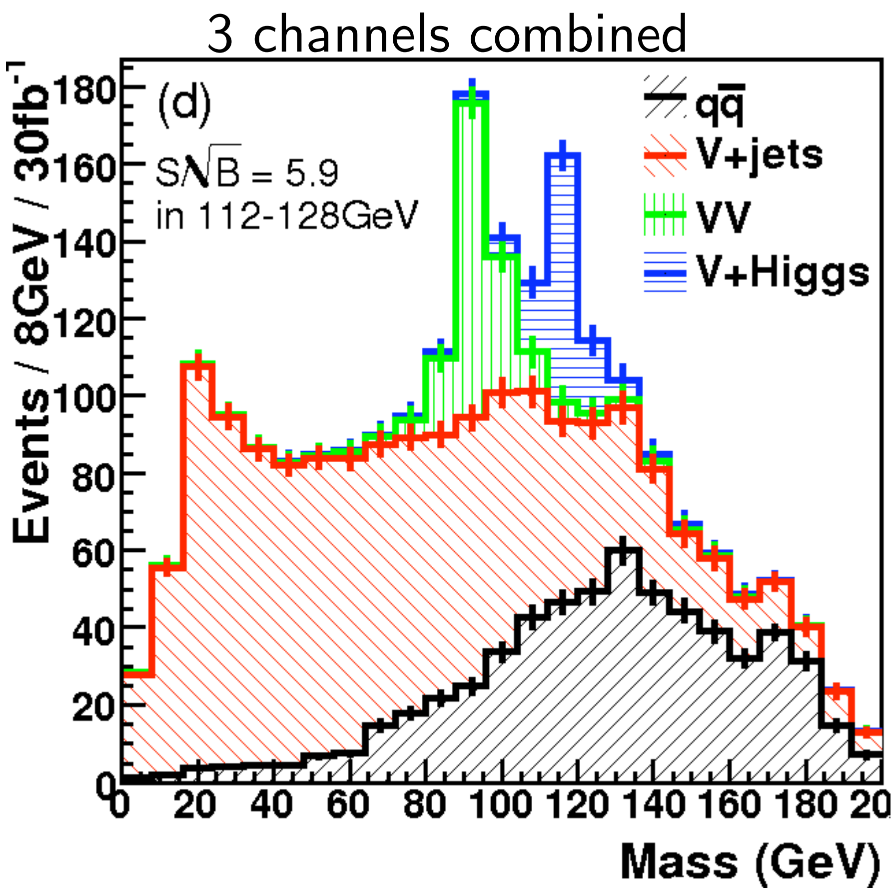
Conclusion [ATLAS TDR]:

The extraction of a signal from H → bb decays in the WH channel will be very difficult at the LHC even under the most optimistic assumptions [...]

Z/W + H (→bb) rescued ?

Boosted Higgs at high p_t: central decay products ⇒ single massive jet

Use jet-finding geared to identify the characteristic structure of fast-moving Higgs that decays into a bb-pair close in angle



- with common & channel specific cuts: p_{tV}, p_{tH} > 200 GeV , ...
- real/fake b-tag rate: 0.7/0.01
- NB: very neat peak for WZ (Z →bb) Important for calibration

Butterworth et al. '08

5.9σ at 30 fb^{-1}: VH with H → bb recovered as one of the best discovery channels for light Higgs? More exp. studies to come !

Conclusions

Impressive progress in perturbative QCD in the last few years

- precision in parton densities
- full automation in LO matrix elements calculations
- NLO: automation on the horizon
- NNLO for standard candle processes available or almost
- all order understanding of IR singularities
- jets: many new ideas, impressive level of sophistication
- ... apologies for all the other important work I could not mention

Still many challenges ahead but QCD theory will provide solid basis for a successful physics program at the LHC

How often did you hear the statement that looking for BSM signals at the LHC might be like looking for a needle in a haystack?

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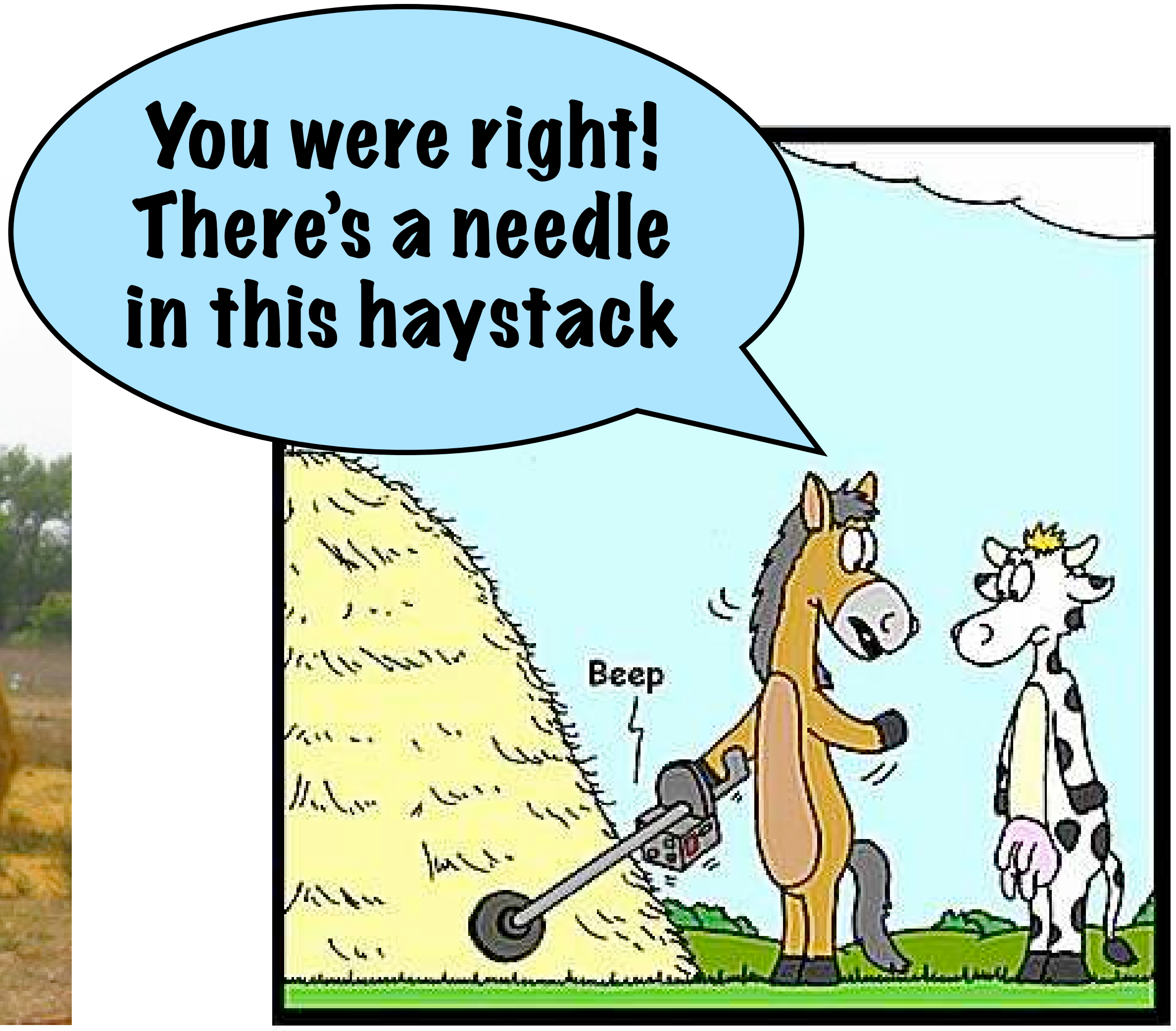

But at the end, it is all a matter of having the right tools.

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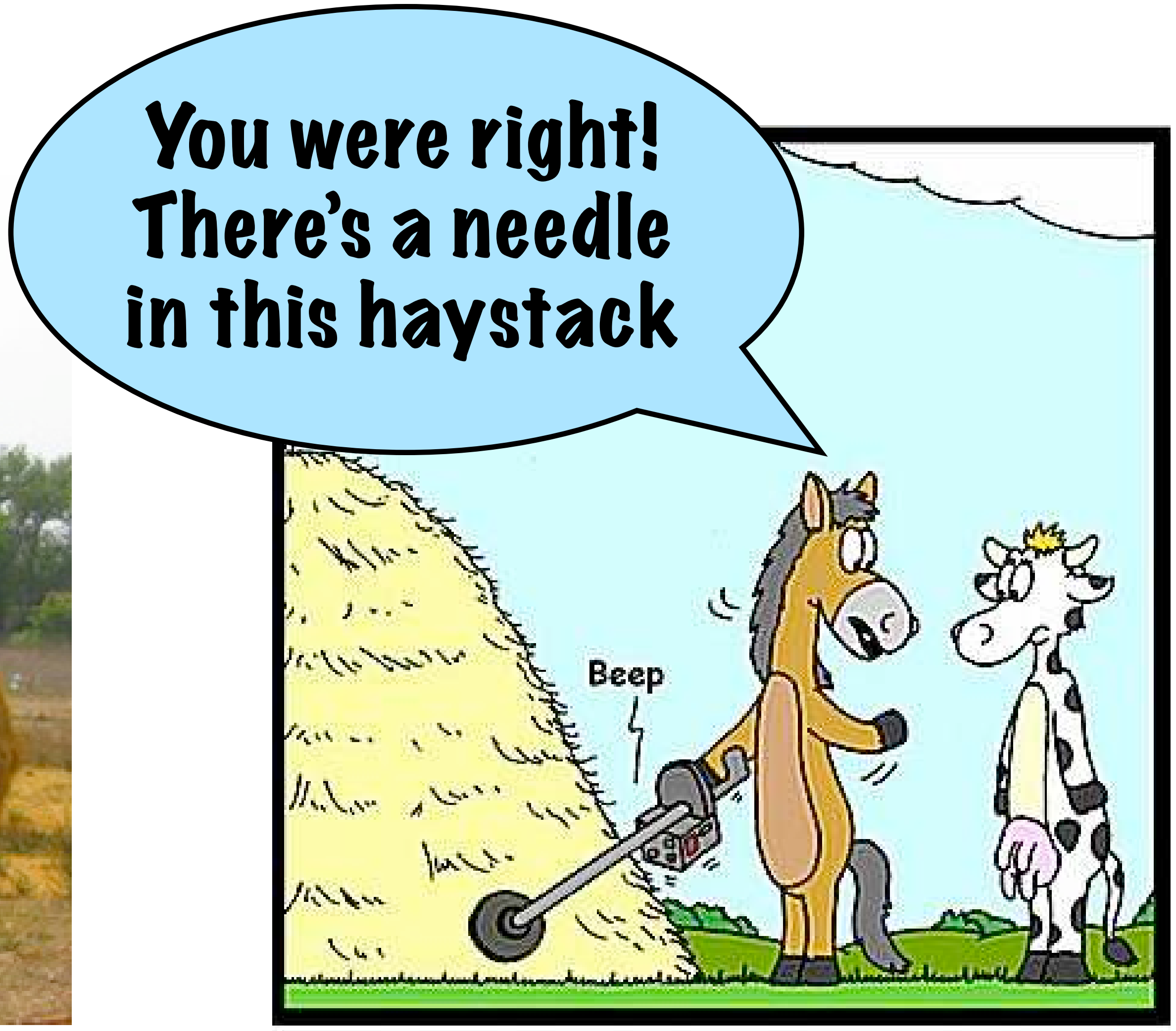

But at the end, it is all a matter of having the right tools.

UNDERSTANDING QCD CRUCIAL TO DEVELOP THE RIGHT TOOLS!