Towards LHC Phenomenology beyond Leading Order

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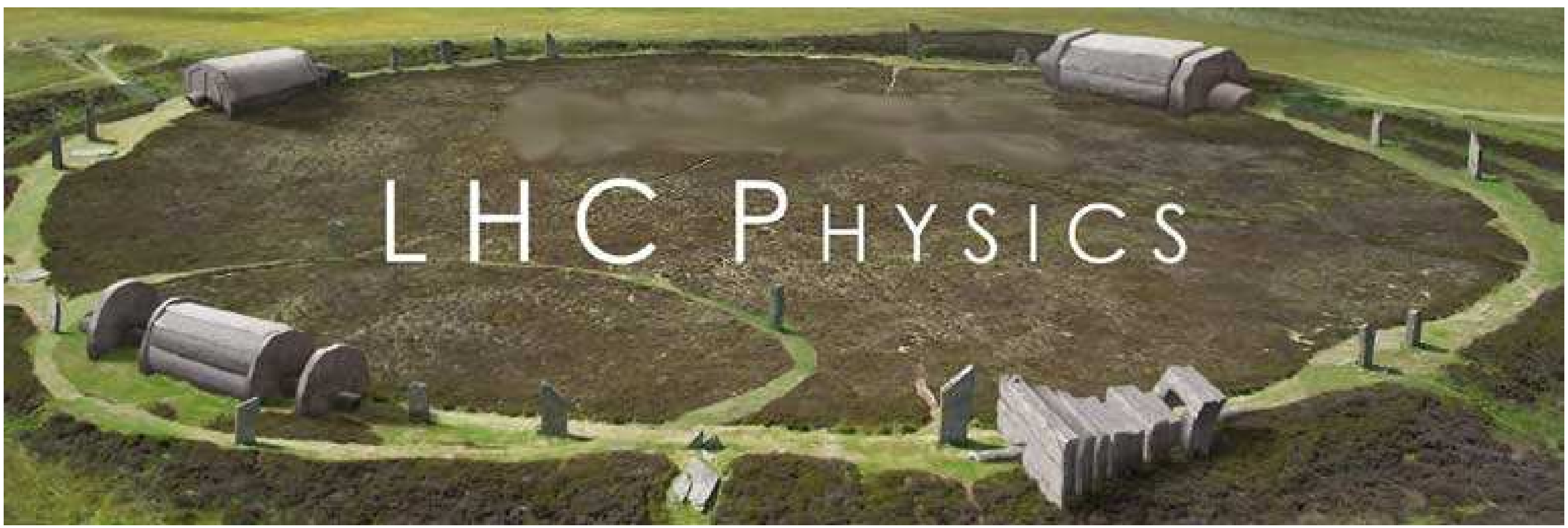
Birmingham, 25.11.09

The LHC . . .

. . . has been planned long time ago . . .



Linear Colliders also seem to have been supported . . .

. . . so why do we say we are entering a New Era in Particle Physics?

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. . . because instead of hunting buffaloes,
we are now hunting Higgs bosons . . .

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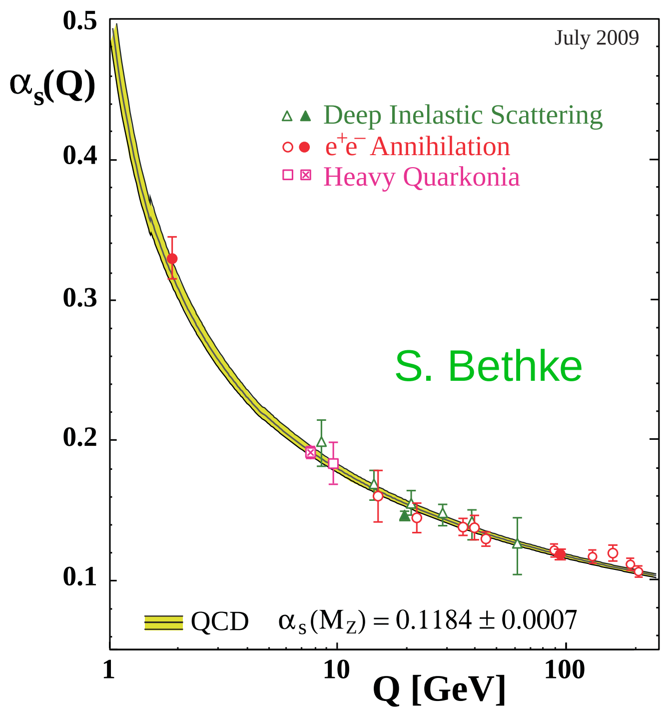
process	events/sec	
QCD jets $E_T > 150$ GeV	100	background
$W \to e\nu$	15	background
$t\bar{t}$	1	background
Higgs, $m_H \sim 130$ GeV	0.02	signal
gluinos, $m \sim 1$ TeV	0.001	signal

strong interactions

basic principles of Quantum Chromo-Dynamics (QCD):

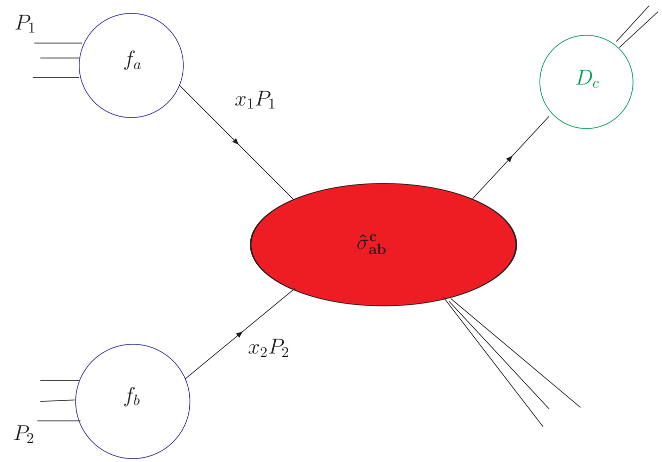
- asymptotic freedom: coupling $\alpha_s(Q^2) \to 0$ for $Q^2 \to \infty$



constituents of hadrons (quarks and gluons) can be considered as freely interacting at high energies (i.e. short distances)

- factorisation: systematic separation of long-distance effects (non-perturbative) and short-distance cross sections (“hard scattering”)

factorisation



$$\sigma_{pp\to X} = \sum_{a,b,c} f_a(x_1,\mu_f^2) f_b(x_2,\mu_f^2) \otimes \hat{\sigma}_{ab}\left(p_1,p_2,\frac{Q^2}{\mu_f^2},\frac{Q^2}{\mu_r^2},\alpha_s(\mu_r^2)\right)$$

$$\otimes D_{c\to X}(z,\mu_f^2) + \mathcal{O}(1/Q^2)$$

f_a, f_b: parton distribution functions (universal), model proton structure

$\hat{\sigma}_{ab}$: partonic hard scattering cross section, calculable order by order in perturbation theory

$D_{c\to X}(z,\mu_f^2)$: describing the final state e.g. fragmentation function, jet observable, etc.

shortcomings of leading order predictions

$\hat{\sigma} = \alpha_s^k(\mu) \left[\hat{\sigma}^{\rm LO} + \alpha_s(\mu)\, \hat{\sigma}^{\rm NLO}(\mu) + \alpha_s^2(\mu)\, \hat{\sigma}^{\rm NNLO}(\mu) + \ldots \right]$

calculation at n-th order: $d\hat{\sigma}^{(n)}/d\ln(\mu^2) = \mathcal{O}(\alpha_s^{n+1})$

truncation of perturbative series at LO

$\Rightarrow$ large renormalisation/factorisation scale dependence

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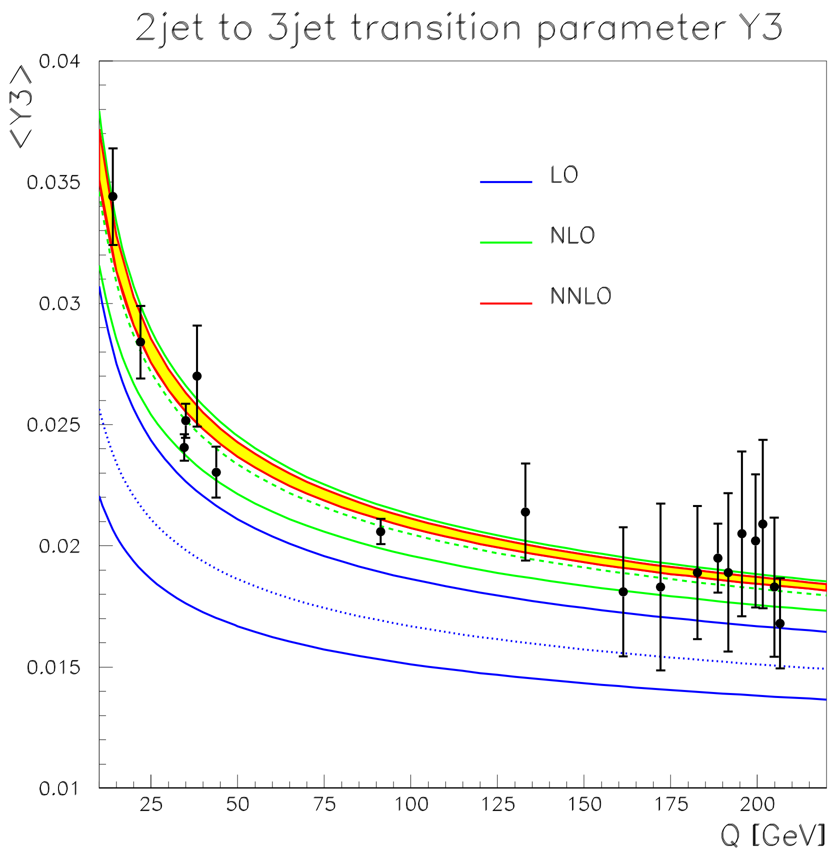


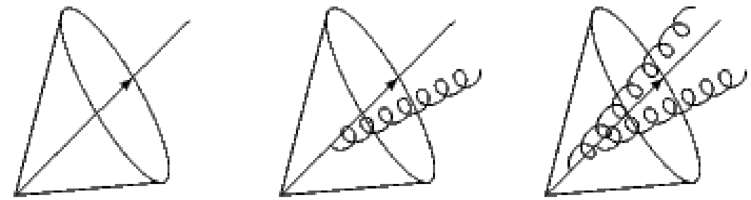
example:

3-jet observable in e^+e^- annihilation [A. Gehrmann-De Ridder, T. Gehrmann, N. Glover, GH '09]

uncertainty bands: $M_Z/2 < \mu < 2\, M_Z$

shortcomings of leading order predictions

- poor jet modelling



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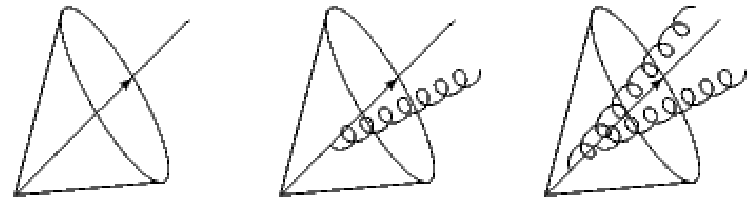

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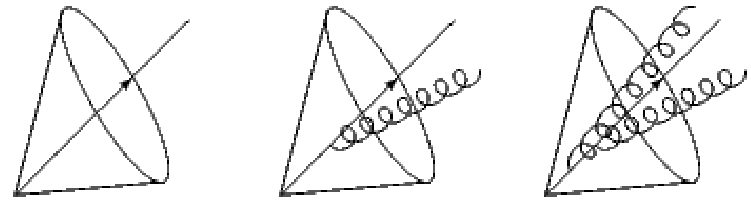

- cases where shapes of distributions are not well predicted by LO
  (new partonic processes become possible beyond LO)
- Minimal Supersymmetric Standard Model (MSSM): would be ruled out already without radiative corrections:
  mass of lightest Higgs boson at LO: $M_h \leq min(M_A, M_Z) \cdot |\cos 2\beta|$
- . . .

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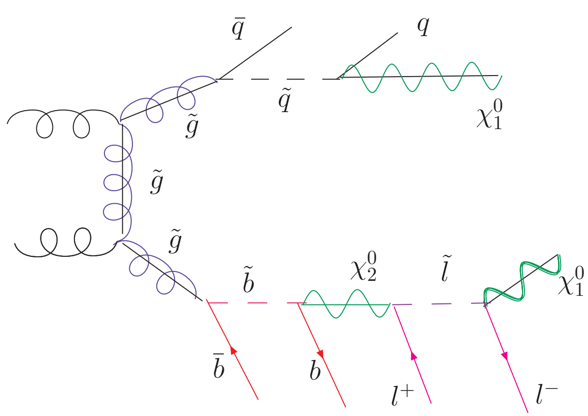
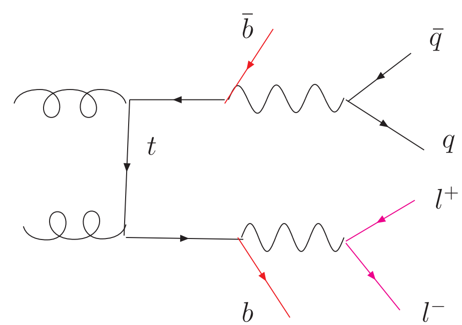
  NLO calculations tedious case-by case exercises
- now paradigm change:
  we are moving towards automated NLO tools

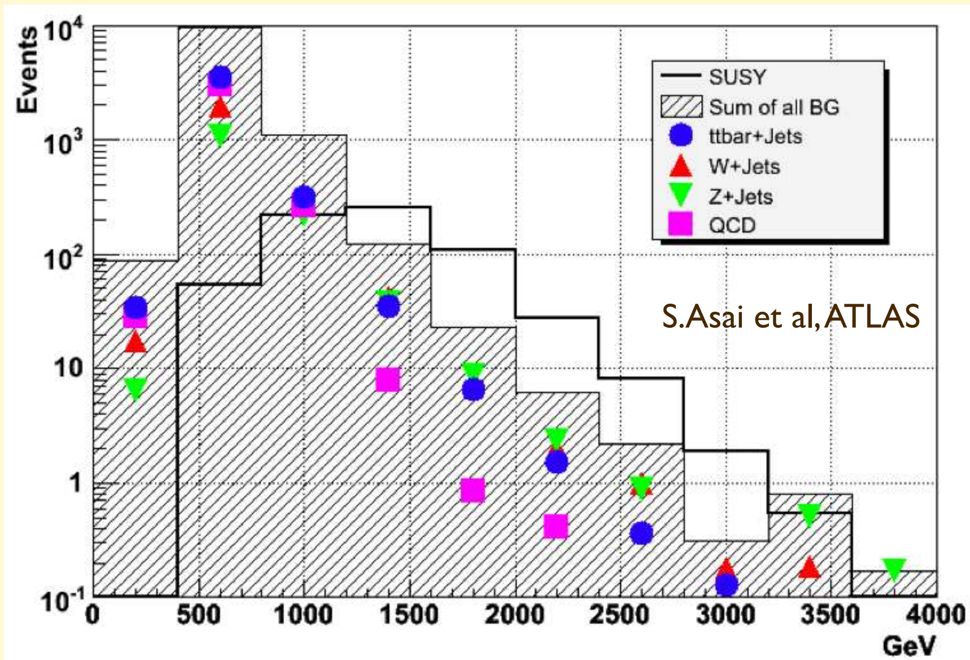
(heavy) SUSY particles:

- decay through cascades emitting quarks and leptons
- signatures: energetic jets and leptons, missing E_T
- QCD radiation generates additional hard jets





Overall result, after the complete detector simulation, etc....



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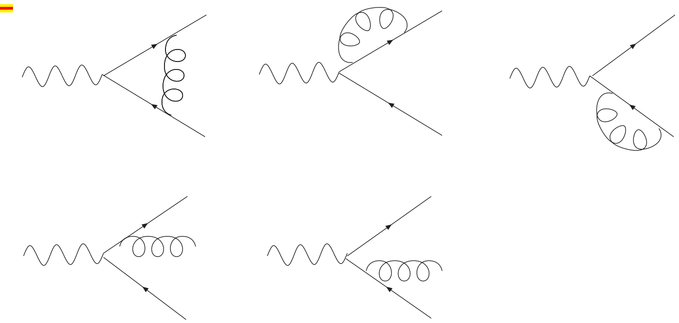
ingredients for m-particle observable at NLO

virtual part (one-loop integrals):



$$\mathcal{A}^V_{NLO} = A_2/\epsilon^2 + A_1/\epsilon + A_0$$

$$d\sigma^V \sim Re\left(\mathcal{A}^\dagger_{LO}\,\mathcal{A}^V_{NLO}\right)$$

real radiation part: soft/collinear emission of massless particles

$\Rightarrow$ need subtraction terms

$$\Rightarrow \int_{\text{sing}} d\sigma^S = -A_2/\epsilon^2 - A_1/\epsilon + B_0$$

$$\sigma^{NLO} = \underbrace{\int_{m+1}\left[d\sigma^R - d\sigma^S\right]_{\epsilon=0}}_{\text{numerically}} + \underbrace{\int_m \left[\underbrace{d\sigma^V}_{\text{cancel poles}} + \underbrace{\int_{\text{s}} d\sigma^S}_{\text{analytically}}\right]_{\epsilon=0}}_{\text{numerically}}$$

Modular structure

Tree Modules		One-Loop Module		IR Modules
$\|\mathcal{A}^{LO}\|^2$	$\oplus$	$2\,Re(\mathcal{A}^{LO\,\dagger}\mathcal{A}^{NLO,V})$	$\oplus$	$\sum_j \int_j \mathcal{S}_j$
$\|\mathcal{A}^{NLO,R}\|^2$			$\ominus$	$\sum_j \mathcal{S}_j$

has been bottleneck so far

NLO complexity

calculations increasingly difficult for more particles in final state

- example for time scale to add one parton:

  $pp \to 2$ jets at NLO (4-point process):
  Ellis/Sexton 1986

  $pp \to 3$ jets at NLO (5-point process):
  Bern et al, Kunszt et al. 1993-95

  $pp \to 4$ jets at NLO (6-point process):
  not yet available

progress

- more efficient techniques to calculate loop amplitudes
  - unitarity-based methods

    e.g. BlackHat, Rocket, CutTools, analytic, . . .
  - improved methods based on Feynman diagrams

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  LO tools can provide:
  - event generation
  - phase space integration
  - histogramming tools
  - subtraction terms for soft/collinear radiation

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  - phase space integration
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  - subtraction terms for soft/collinear radiation
- matching NLO amplitudes with parton showers
  e.g. MC@NLO, POWHEG, . . .

2009 status of NLO wishlist for LHC

$pp \to W\,W$ jet	Denner et al.; Ellis et al.
$pp \to Z\,Z$ jet	Binoth/Gleisberg/Karg/Kauer/Sanguinetti
$pp \to t\bar{t}\,b\bar{b}$	Bredenstein et al.; Bevilacqua et al.
$pp \to t\bar{t} + 2$ jets	
$pp \to Z\,Z\,Z$	Lazopoulos/Melnikov/Petriello; Hankele/Zeppenfeld
$pp \to V\,V\,V$	Binoth/Ossola/Papadopoulos/Pittau; Zeppenfeld et al.
$pp \to V\,V\,b\bar{b}$	
$pp \to W\,\gamma$ jet	Campanario/Englert/Spannowsky/Zeppenfeld
$pp \to V\,V + 2$ jets	VBF: Bozzi/Jäger/Oleari/Zeppenfeld, VBFNLO coll.
$pp \to W + 3$ jets	BlackHat coll.; Ellis/Giele/Kunszt/Melnikov/Zanderighi*
$pp \to Z + 3$ jets	BlackHat collaboration
$pp \to b\bar{b}b\bar{b}$	Binoth/Guffanti/Guillet/Reiter/Reuter
$pp \to t\,\bar{t}$ jet	Dittmaier/Uwer/Weinzierl
$pp \to t\,\bar{t}\,Z$	Lazopoulos/McElmurry/Melnikov/Petriello
$pp \to b\,\bar{b}\,Z\,,\,b\,\bar{b}\,W$	Febres Cordero/Reina/Wackeroth

● done ● partial results * leading colour only

Interface

details worked out at Les Houches 2009 workshop on TeV colliders

Monte Carlo tool (MC) | One-Loop-Provider (OLP)

initialisation:

process info
CH summed

model parameters
fix scheme

...

order →

copy/confirm

← contract

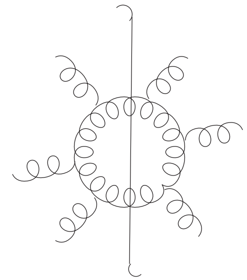
runtime:

events ⇄ $A_2, A_1, A_0, |Born|^2$

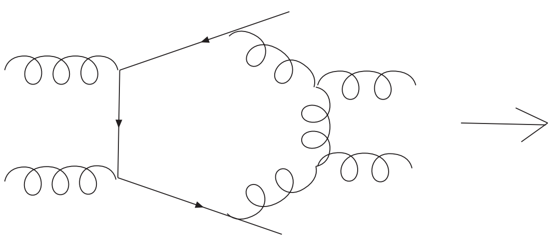
standard interface

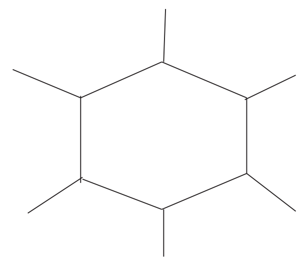
One-loop methods

- unitarity based:

$$\mathcal{A} = \sum_{\text{cuts}} \int d\,PS$$  $$+ \quad \mathcal{R}$$

- Feynman diagram based

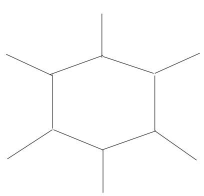




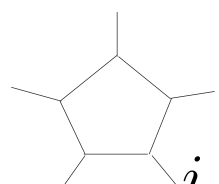
$+$ integrals with less legs

non-trivial tensor structure

scalar 6-point function



$$= \sum_{i=1}^{6} b_i$$



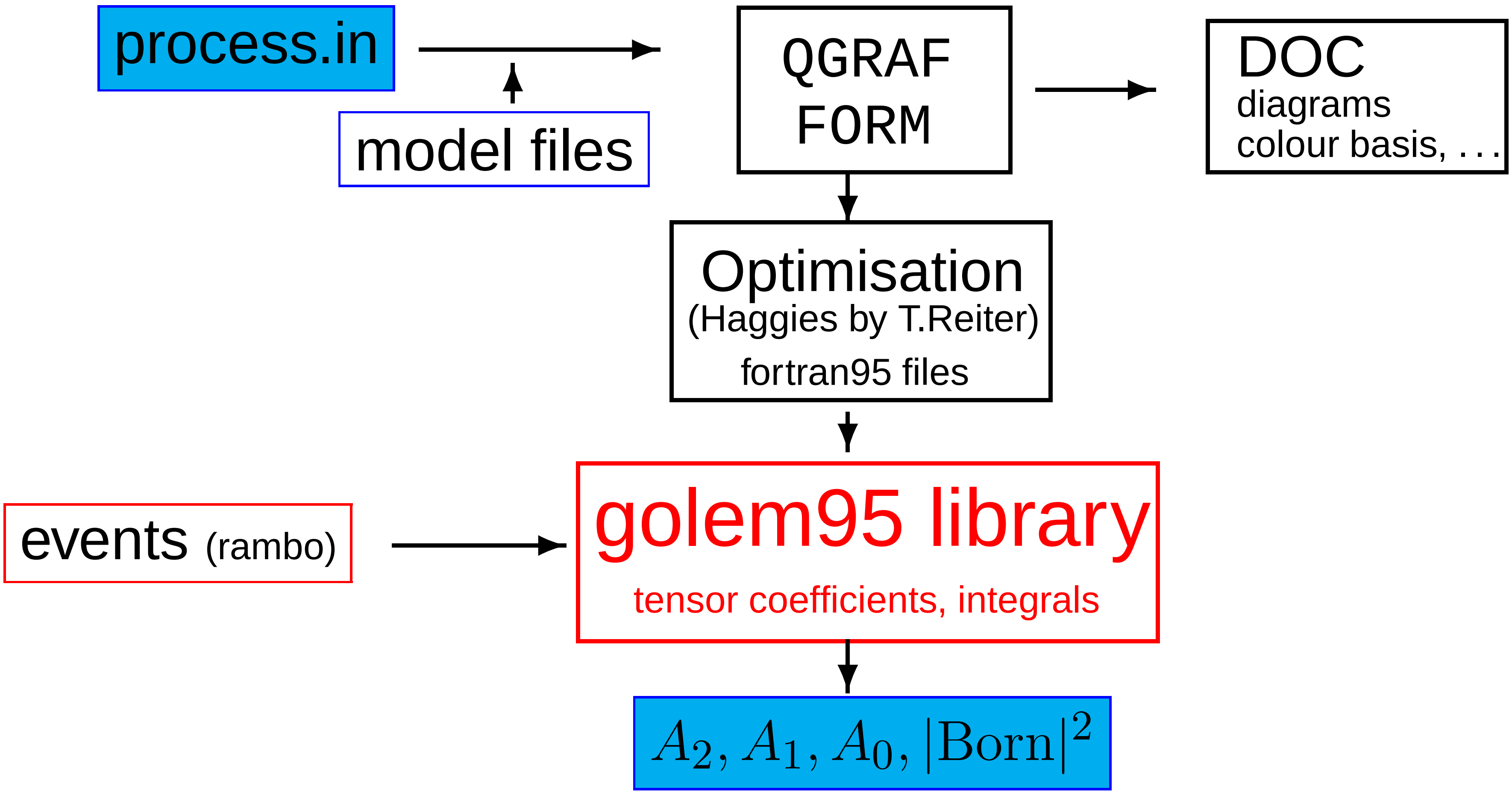
$$i \qquad \ldots$$

reduction to set of basis integrals (4-, 3- and 2-point functions)

GOLEM

General One-Loop Evaluator of Matrix elements

[Binoth, Cullen, Guillet, GH, Karg, Kauer, Pilon, Reiter, Rodgers, Wigmore]



Golem strong points

- can deal with an arbitrary number of mass scales
  link LoopTools for finite massive boxes
- colour does not add additional complexity
- rational parts are "for free"
- efficient use of recursive structure
  caching system
- projection onto helicity states
  exploit spinor helicity techniques, gauge cancellations, smaller building blocks
- collaboration has several independent programs
  $\Rightarrow$ strong checks
- can avoid spurious singularites from
  Gram determinants $\Rightarrow$ numerically robust

Golem development

- Golem results:
  $pp \to WW, ZZ, \gamma\gamma j, HH, HHH, Hjj$ (interference)
  $ZZj, b\bar{b}b\bar{b}$

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  $pp \to WW, ZZ, \gamma\gamma j, HH, HHH, Hjj$ (interference)
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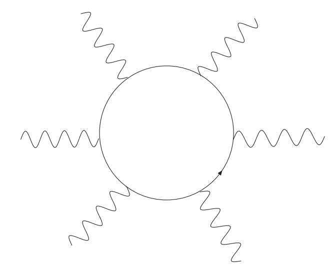
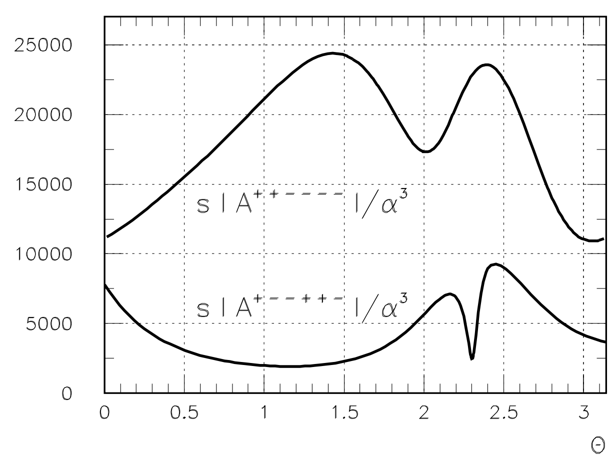
- under construction:
  - allow for complex masses $\Rightarrow$ deal with unstable particles
  - validation for multi-leg calculations within supersymmetric models [GH, T. Kleinschmidt, M. Rodgers]
  - interface to `FeynRules`, producing model files from arbitray Lagrangians [C. Duhr et al.]
  - user-friendly public interface, detailed documentation
  - combination with parton shower [Sherpa, F. Krauss et al.]

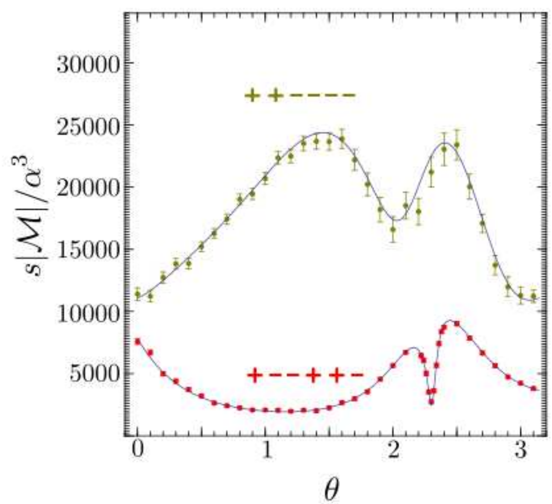
six-photon amplitude

[Mahlon 94] (special helicity configurations only)
[Nagy, Soper 06; Gong, Nagy, Soper 08] (numerically)
[Binoth, Gehrmann, GH, Mastrolia 07]
[Ossola, Pittau, Papadopoulos 07]
[Bernicot, Guillet 08]



- rational parts shown to be zero [Binoth, Guillet, GH 06]
- used both unitarity cuts and Golem

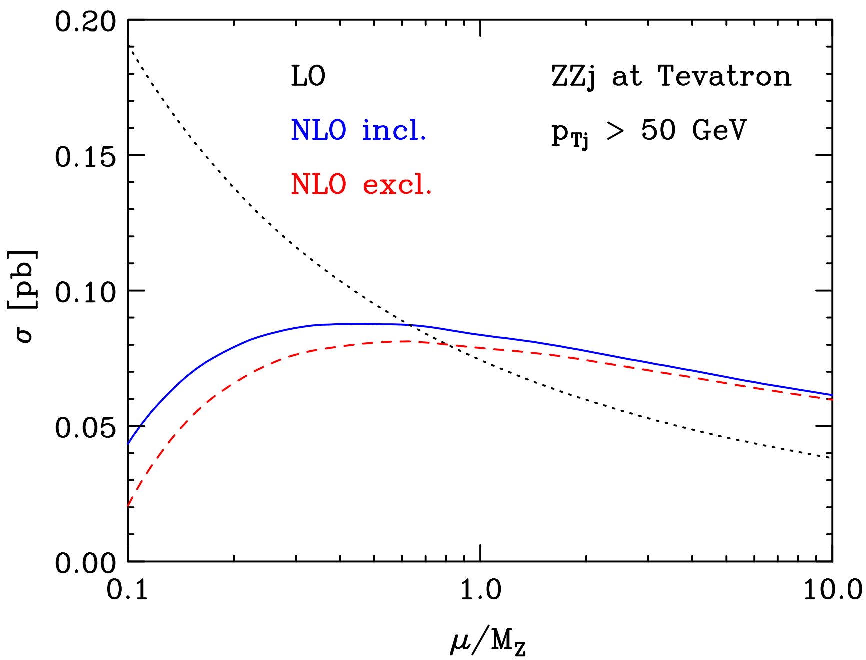


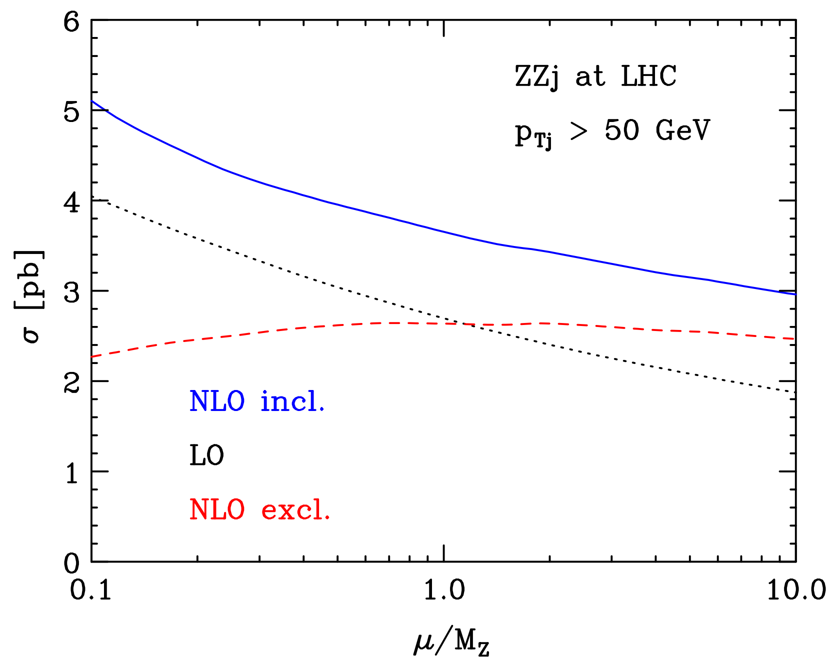


Gong, Nagy, Soper

ZZ + jet production: scale dependence

T. Binoth, T. Gleisberg, S. Karg, N. Kauer, G. Sanguinetti '09





NLO excl.: jet veto: no additional jets with $p_T > 50$ GeV

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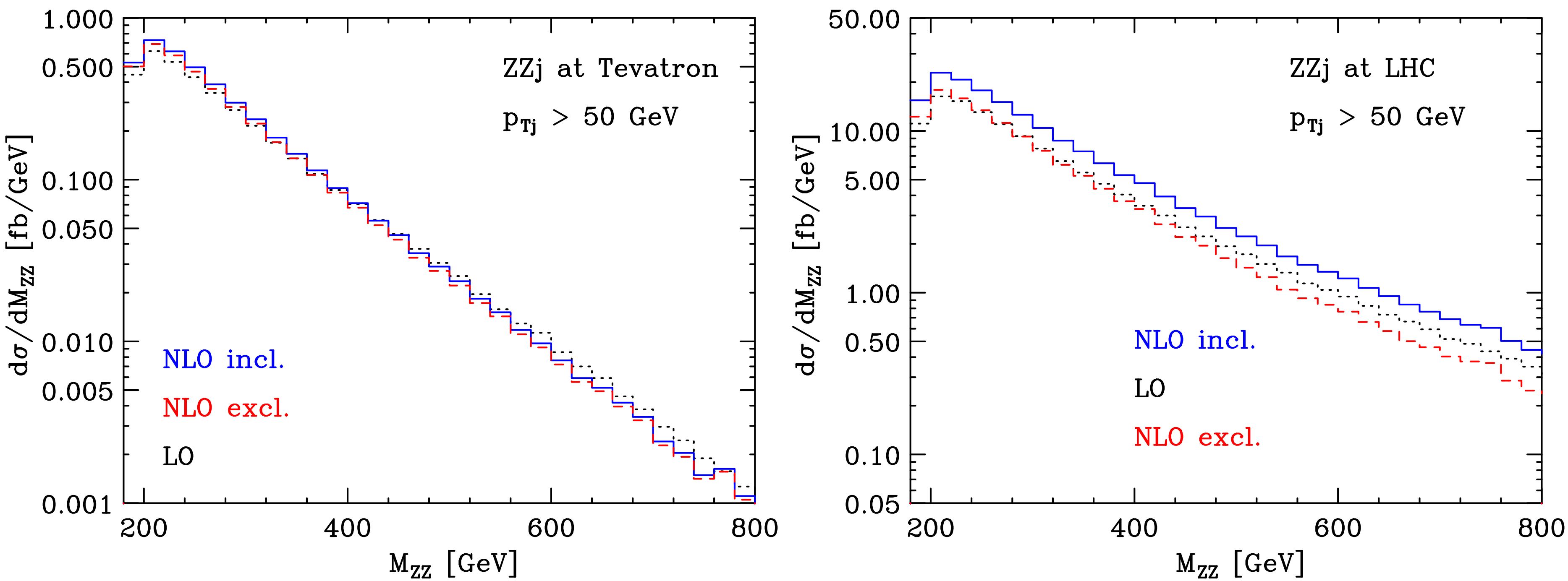
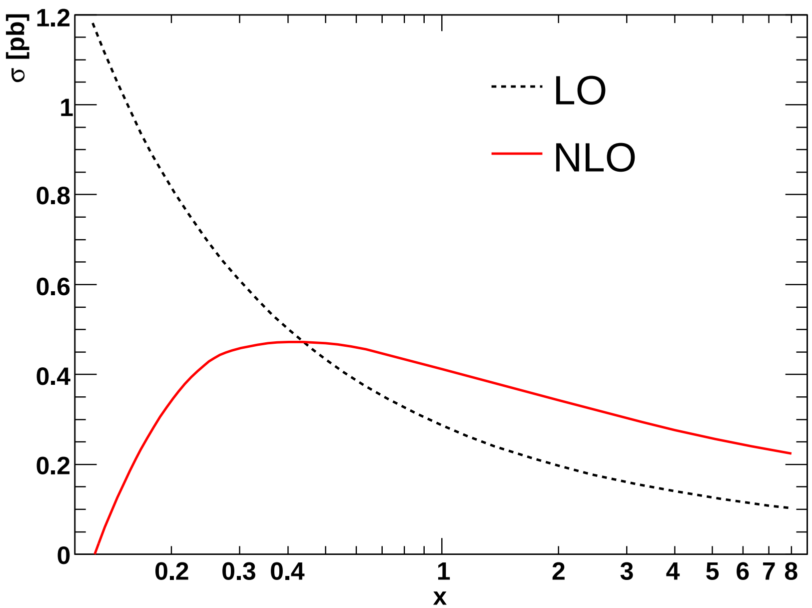
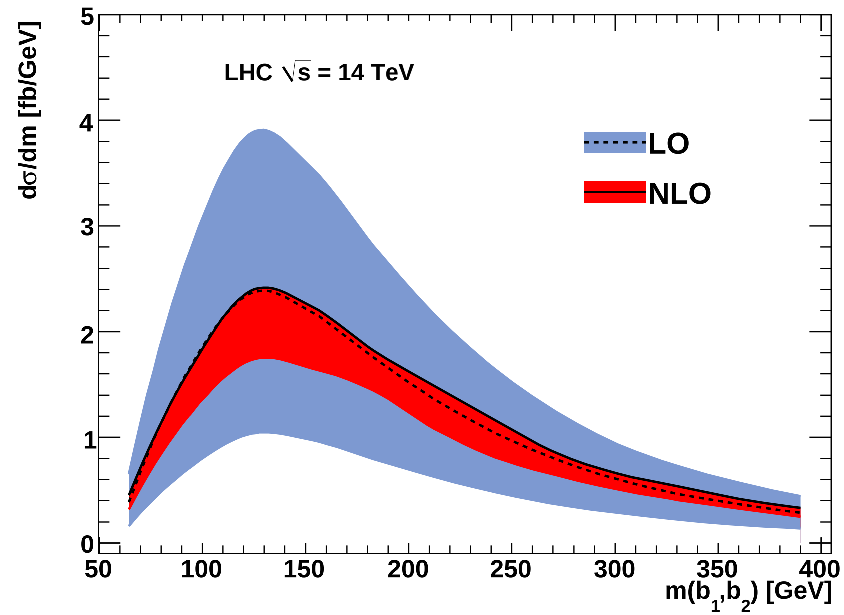


$pp \to b\bar{b}b\bar{b}$ at NLO

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

[Binoth, Greiner, Guffanti, Guillet, Reiter, Reuter '09]





prompt photons

The PHOX Family

NLO Monte Carlo programs (partonic event generators) to calculate cross sections for the production of large-p_T photons, hadrons and jets

http://wwwlapp.in2p3.fr/lapth/PHOX_FAMILY/main.html

F. Arleo, P. Aurenche, T. Binoth, M. Fontannaz, J.Ph. Guillet, GH, E. Pilon, M. Werlen

- DIPHOX

  $h_1\, h_2 \to \gamma\ \gamma\ + X$, $h_1\, h_2 \to \gamma\ h_3\ + X$, $h_1\, h_2 \to h_3\, h_4\ + X$

- JETPHOX

  $h_1\, h_2 \to \gamma$ jet $+ X$, $h_1\, h_2 \to \gamma\ + X$

  $h_1\, h_2 \to h_3$ jet $+ X$, $h_1\, h_2 \to h_3 + X$

- EPHOX

  $\gamma\, p \to \gamma$ jet $+ X$, $\gamma\, p \to \gamma\ + X$

  $\gamma\, p \to h$ jet $+ X$, $\gamma\, p \to h + X$

- TWINPHOX

  $\gamma\, \gamma \to \gamma$ jet $+ X$, $\gamma\, \gamma \to \gamma\ + X$

PHOX programs

partonic event generators

- produce ntuples (PAW) or histograms
- fragmentation component included fully at NLO
- new: Frixione isolation criterion is being implemented
  designed to suppress fragmentation component

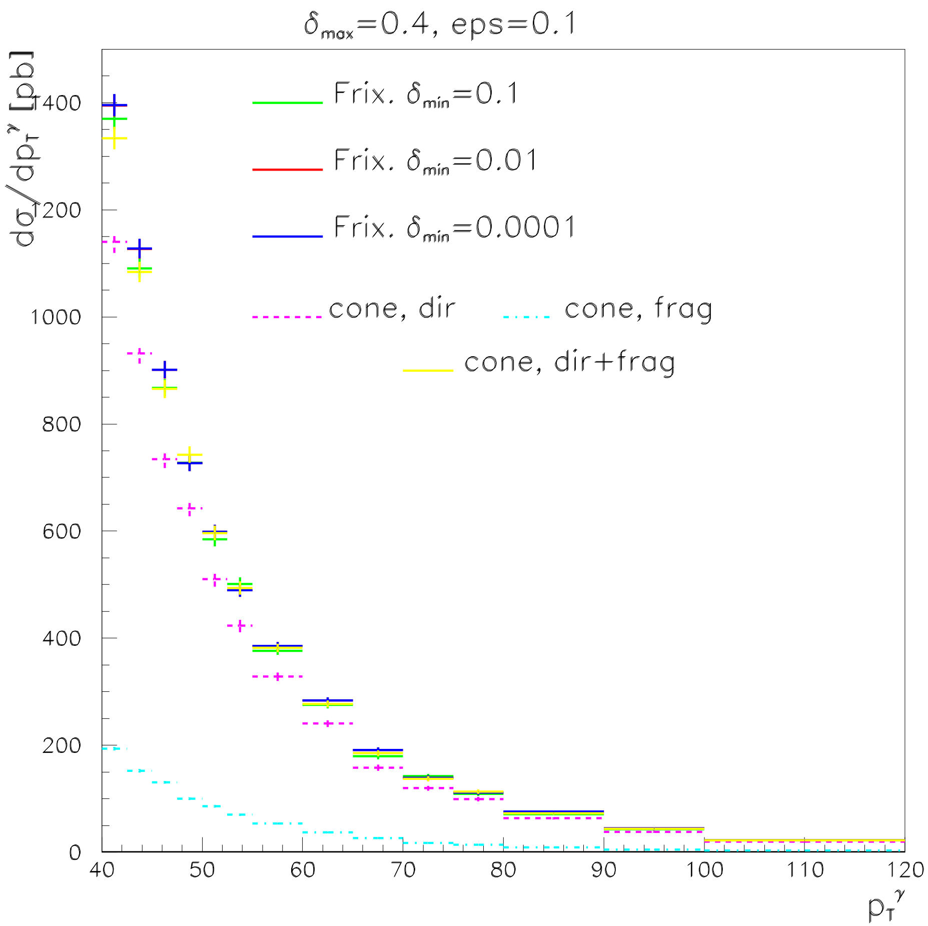
$$E_{T,\max} = \epsilon_\gamma \, p_T^\gamma \underbrace{\left(\frac{1-\cos\delta}{1-\cos\delta_{\max}} \right)^n}_{f(\delta)}$$

$\lim_{\delta \to 0} f(\delta) = 0$

but: no hadronic energy in isolation cone experimentally never realised $\Rightarrow$ better:

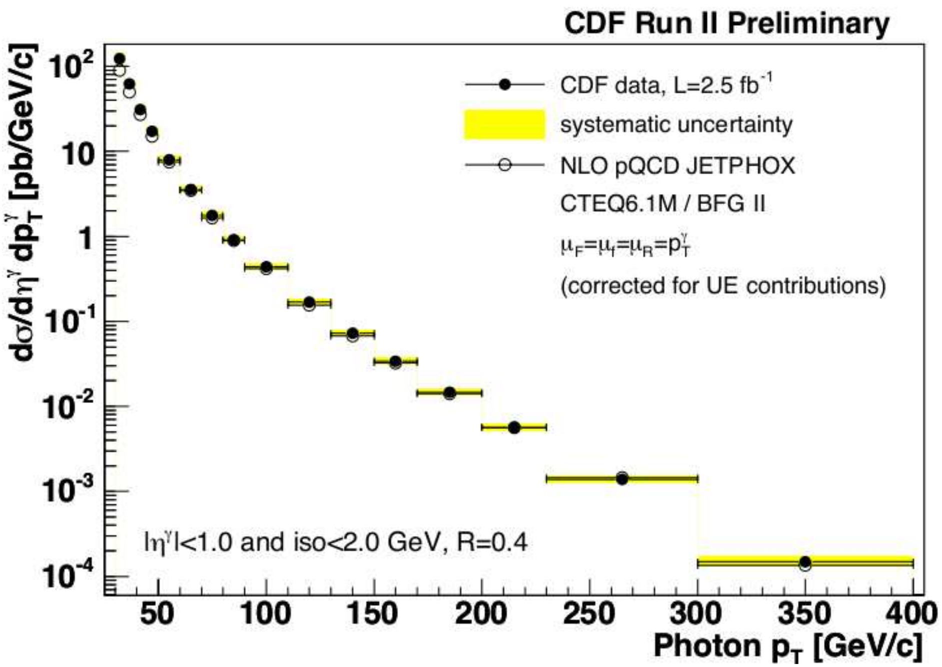
$$f(\delta) = \begin{cases} f(\delta) & \text{for} \quad \delta > \delta_{\min} \\ f(\delta_{\min}) & \text{for} \quad \delta \leq \delta_{\min} \end{cases}$$

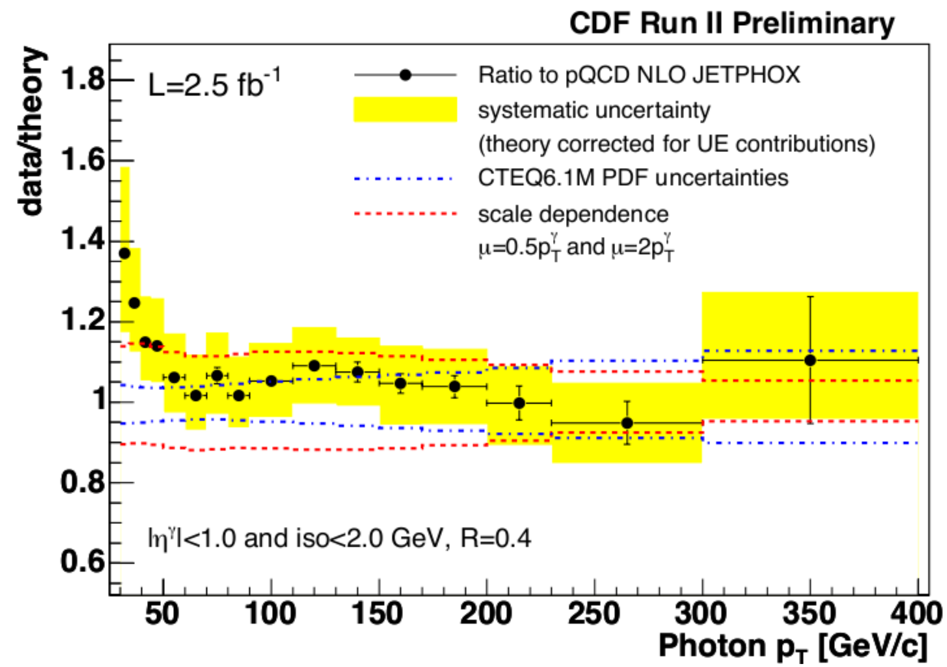
Frixione isolation



even better: "onion type cones" (now being implemented)
six cones of radius 0.1 to 0.4 in steps of 0.05

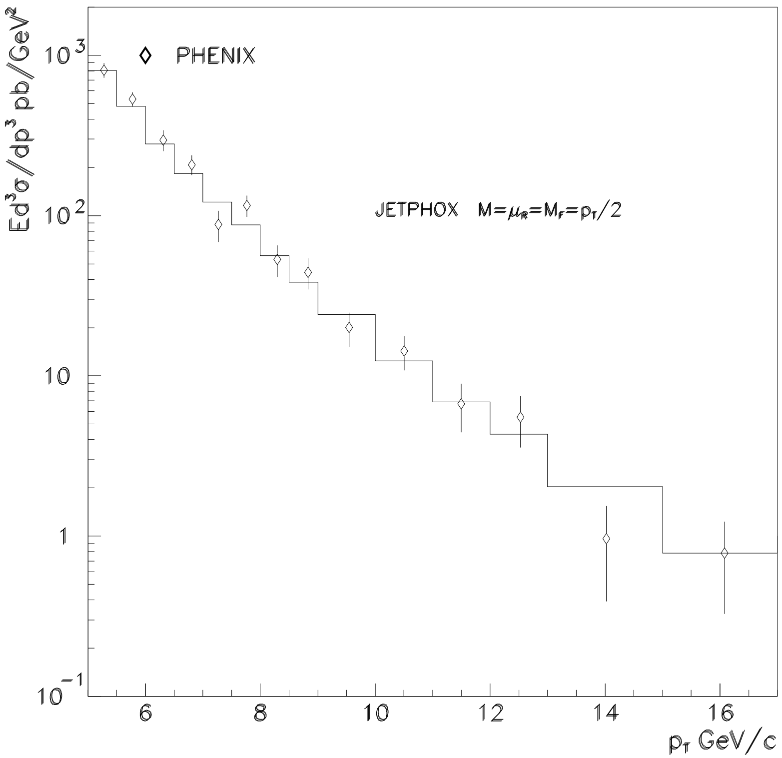
Prompt photons at CDF





$$p_T^\gamma > 30\,\text{GeV},\ E_{T,\max} = 2\,\text{GeV},\ R = 0.4$$

Prompt photons at RHIC



two different methods of photon isolation

(a) cone: $\epsilon_\gamma = 0.1, R = 0.5$

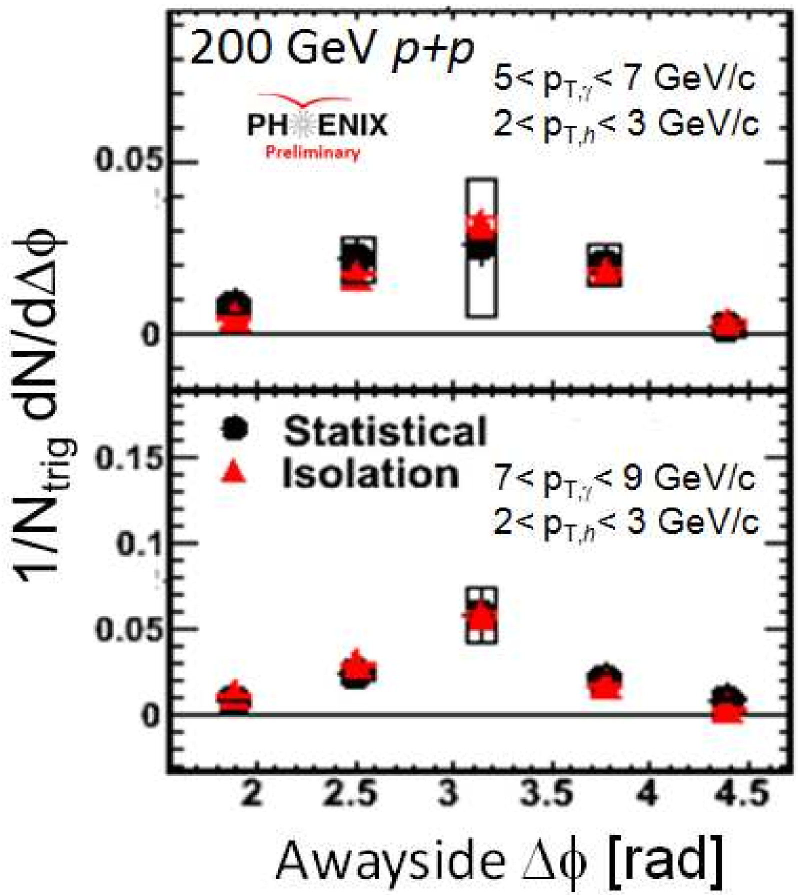
(b) statistical:

direct photon yield Y_{dir}

$$Y_{dir} = \frac{r_\gamma Y_{incl} - Y_{decay}}{r_\gamma - 1}$$

$$r_\gamma = \frac{(\gamma/\pi^0)^{\mathrm{data}}}{(\gamma/\pi^0)^{\mathrm{sim}}}$$

photon isolation at RHIC



$\Delta\phi$: azimuthal angle between photon and charged hadrons

Summary

- in order to understand "New Physics" at TeV colliders: theory predictions for signals and backgrounds must be well under control

  need accuracy beyond Leading Order

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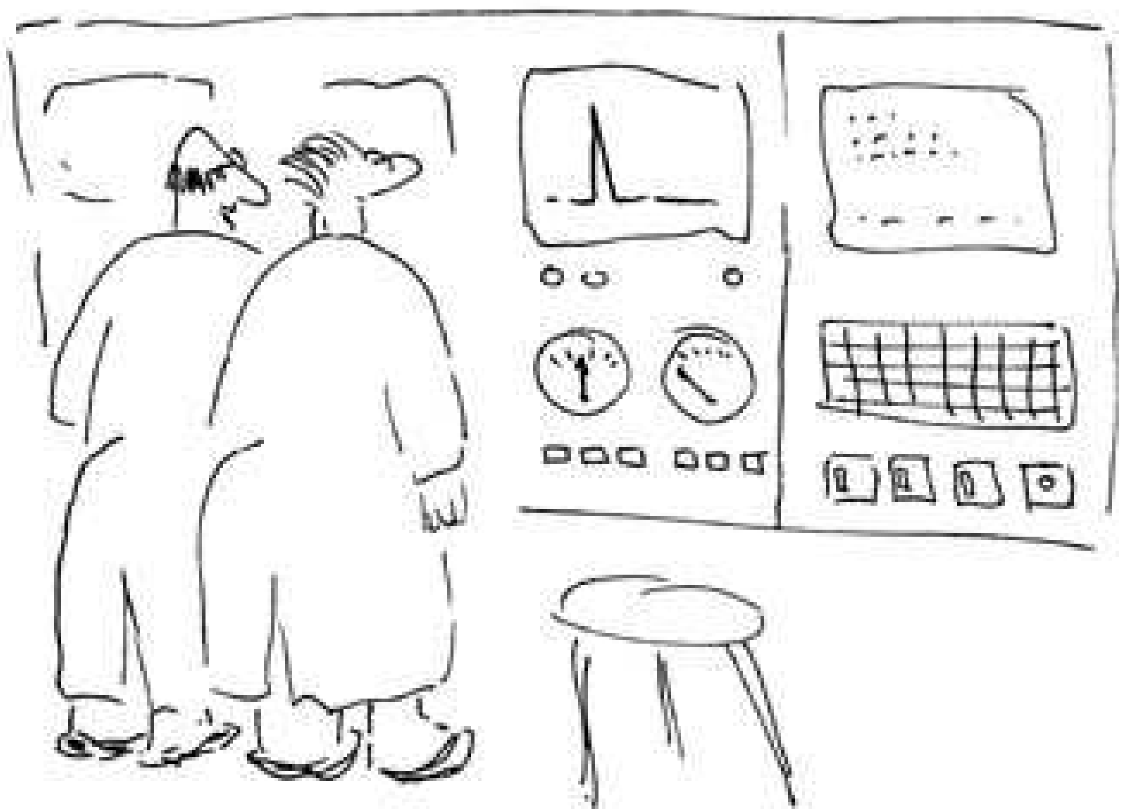
  need accuracy beyond Leading Order

- we are moving towards automated tools for NLO predictions

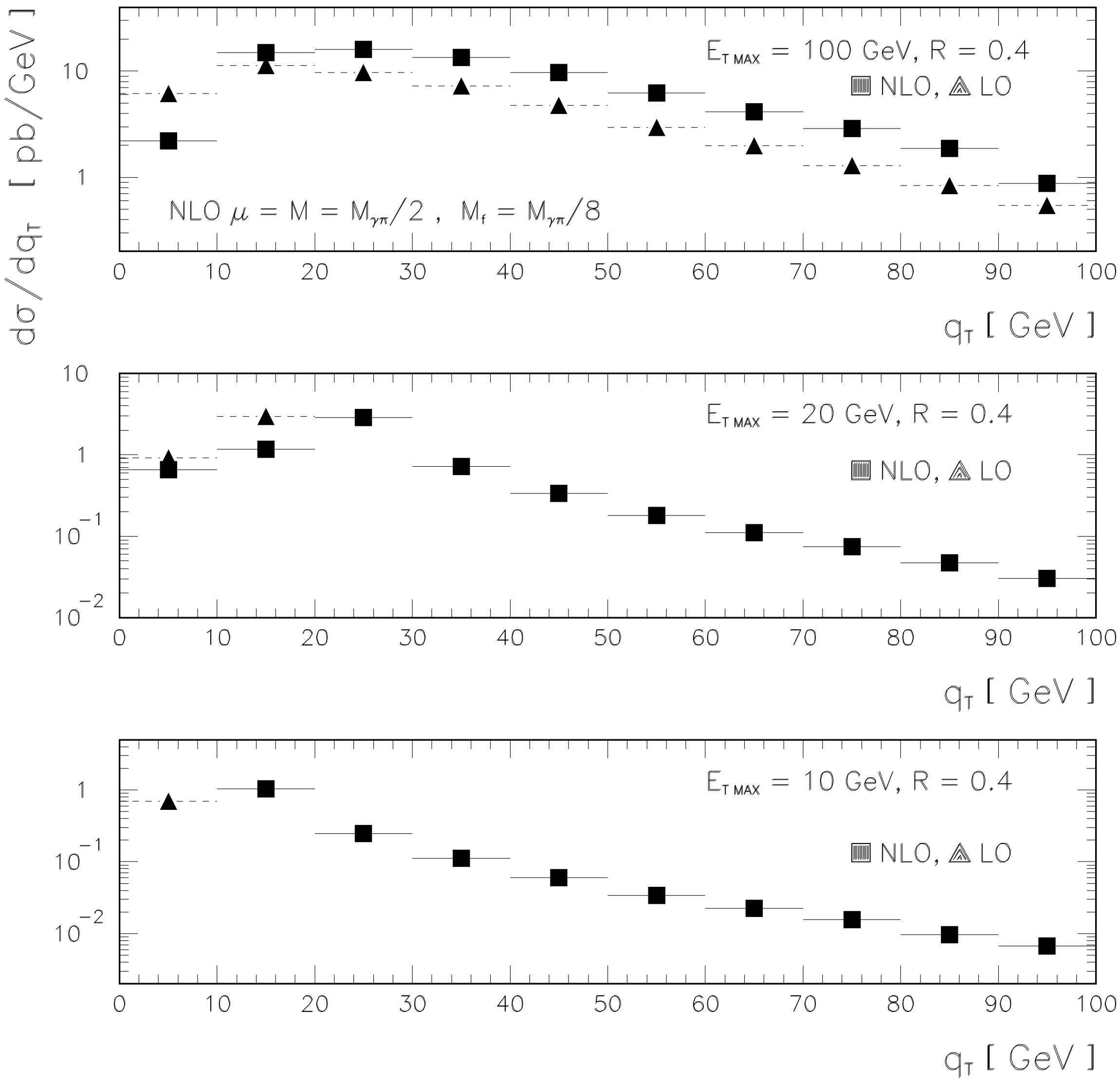
  GOLEM approach:
  - setup valid for massive and massless particles
  - keeps spin information
  - combination with parton shower in progress
  - tensor integral library publicly available at http://lappweb.in2p3.fr/lapth/Golem/golem95.html



"Well, either we've found the Higgs boson, or Fred's just put the kettle on"

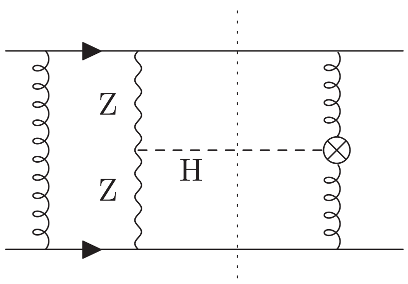
backup slides

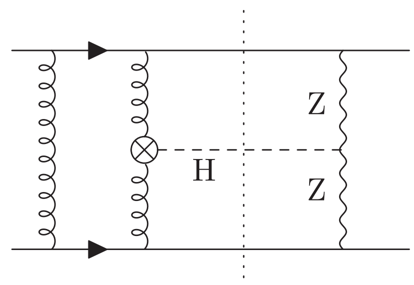
phase space effects enhanced by cuts

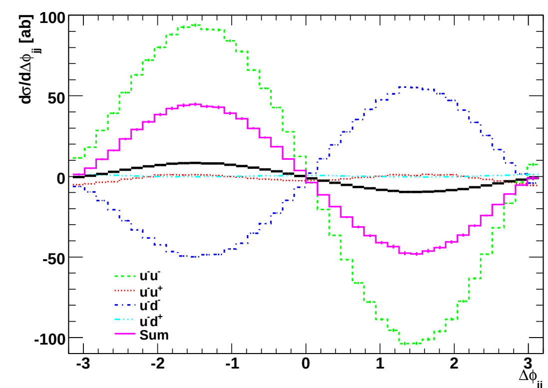


Higgs+2 jet one-loop interference

- semi-numerical approach does best
- example: one-loop interference between vector-boson fusion and gluon fusion in Higgs+2 jet production
  [Andersen, Binoth, GH, Smillie 07]



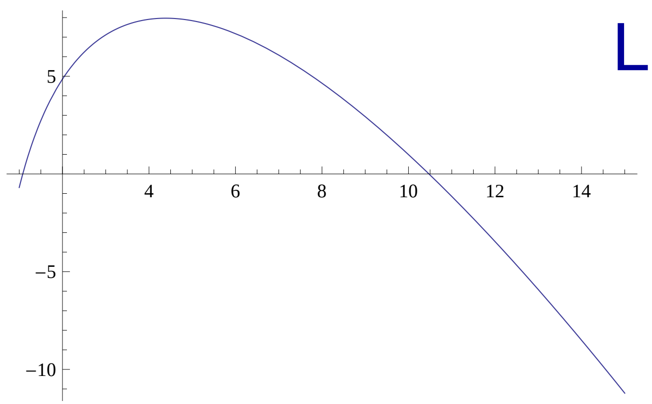




- investigate impact of interference on extraction of HZZ coupling from Higgs+2jet events
- calculation of new master integrals involving several mass scales

asymptotic complexity

- unitarity based methods:
  complexity of colour ordered amplitudes:
  $$\tau_{\text{tree}} \times \tau_{\text{cuts}} \sim N^4 \times \binom{N}{5} \xrightarrow{\text{N large}} N^9$$
- Feynman diagram reduction:
  $$\tau_{\text{diagrams}} \times \tau_{\text{form factors}} \sim 2^N \times \Gamma(N)$$



$\text{Log}(N^9/(\Gamma(N)\,2^N))$

comparison to unitarity methods

NLO results presented at the RADCOR 2009 conference:

number of talks presenting results:

Unitarity methods: 4

($W+3$ jets, $Z+3$ jets, $t\bar{t}b\bar{b}$, cut constructible part of $H+2$ jets)

Feynman diagrams: 8 + all SUSY/BSM (4) + all electroweak corrections (3)

($WWj, ZZj, t\bar{t}b\bar{b}, b\bar{b}b\bar{b}, WW\gamma, ZZ\gamma, W\gamma j, W\gamma\gamma, W\,b\bar{b}, Z\,b\bar{b}, VVjj$ + EW + BSM)

note:

unitarity methods prefer low number of mass scales

Future: expect to discover new heavy particles $\Rightarrow$ rather need more mass scales . . .