Introduction to new staff member

Radja Boughezal

Past and Future

Argonne
NATIONAL LABORATORY

highlights of past work:

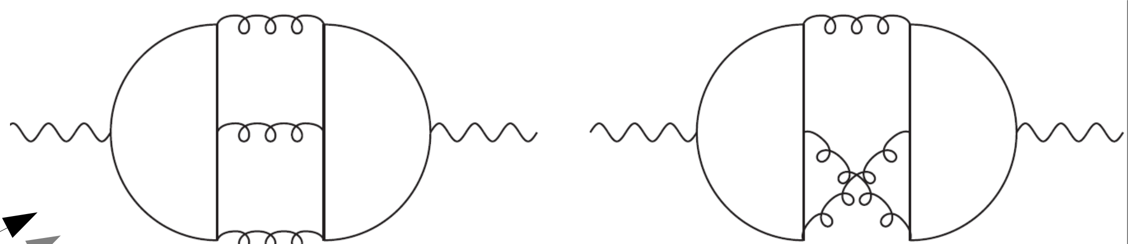
Determining fundamental parameters of the SM

Charm and Bottom quark masses

- Past work aimed to develop deep understanding of the SM at higher orders in perturbation theory

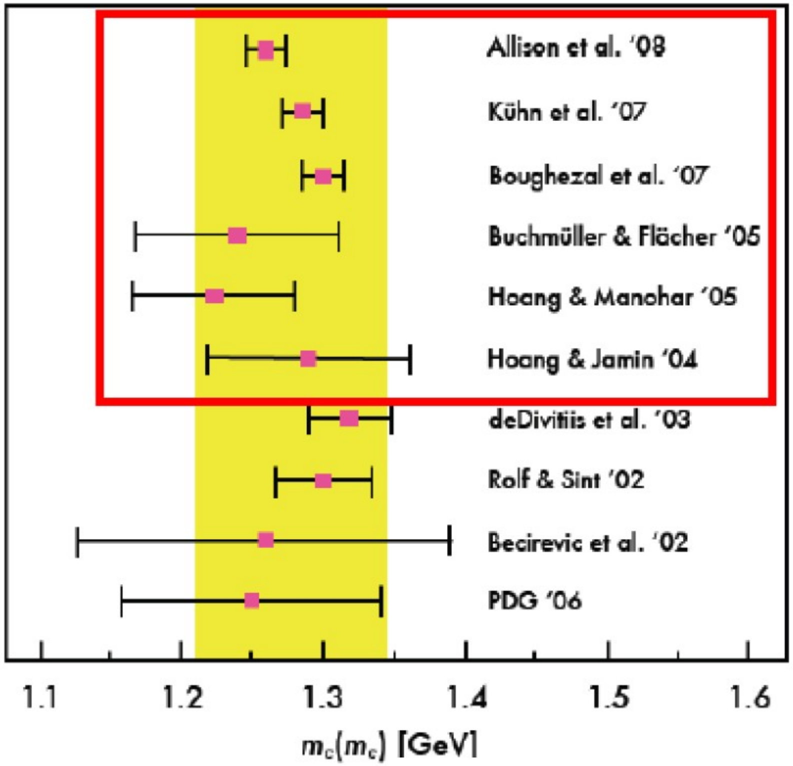
- Used R(s) to determine charm and bottom quark mases; these are fundamental SM parameters essential for a detailed study of the flavour sector

$$R(s) = \frac{\sigma(e^+e^- \to \text{had.})}{\sigma(e^+e^- \to \mu^+\mu^-)} \quad \Leftrightarrow \quad R(s) = 12\pi \mathrm{Im}\Pi(q^2 = s + i\epsilon)$$



Photon vacuum polarization

Boughezal, Czakon, Schutzmeier (2006)



$$\Pi_h(q^2) = Q_h^2 \frac{3}{16\pi^2} \sum_{n>0} \overline{C}_n z^n, \qquad z = \frac{q^2}{4m^2(\mu)}$$

PDG

[BOUGHEZAL 2006 (PHRVA,D74,074006)]

Physical Review **D74** (2006) 074006

BOUGHEZAL 2006 **Charm- and Bottom-Quark Masses from Perturbative QCD**

R. Boughezal M. Czakon, T. Schutzmeier,

	Measurement		(Unit)	Particle (Section)	Observable	
used	1.295 ± 0.015		(GeV)	*c*	*c*-QUARK MASS	1
	$\overline{MS}$ *MASS (GeV)*	*1S MASS (GeV)*				
used	4.205 ± 0.058	4.68 +-0.06	(GeV)	*b*	*b*-QUARK MASS	2
used	4.68 ± 0.06		(GeV)	*b*	*b*-QUARK MASS	

1 BOUGHEZAL 2006 result comes from the first moment of the hadronic production cross-section to order α_s^3.

2 BOUGHEZAL 2006 $\overline{\mathrm{MS}}$ scheme result comes from the first moment of the hadronic production cross-section to order α_s^3. We have converted it to the 1S scheme.

Electroweak Observables

- Provided 3-loop EW corrections to determine previously unknown, potentially large,

Corrections to M_W, $\sin^2\theta_W$, $\delta\rho$ ⇒ Parametrically enhanced corrections that scale like mH^4

Boughezal, Tausk, Van der Bij (2005)

- studied QCD effects with 4-loop accuracy on MW and the effective leptonic weak mixing angle

$$\Delta^{(4)} M_W = -2MeV, \Delta^{(4)} \sin^2\theta^{\text{lept}}_{\text{eff}} = 1.15 \times 10^{-5}$$

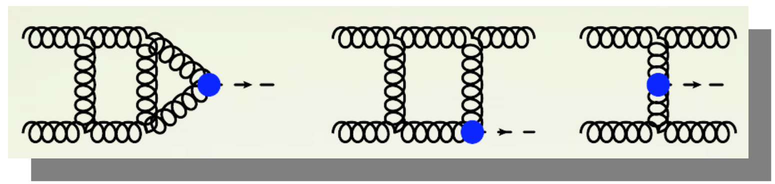
Comparable to expected experimental precision at future lepton colliders

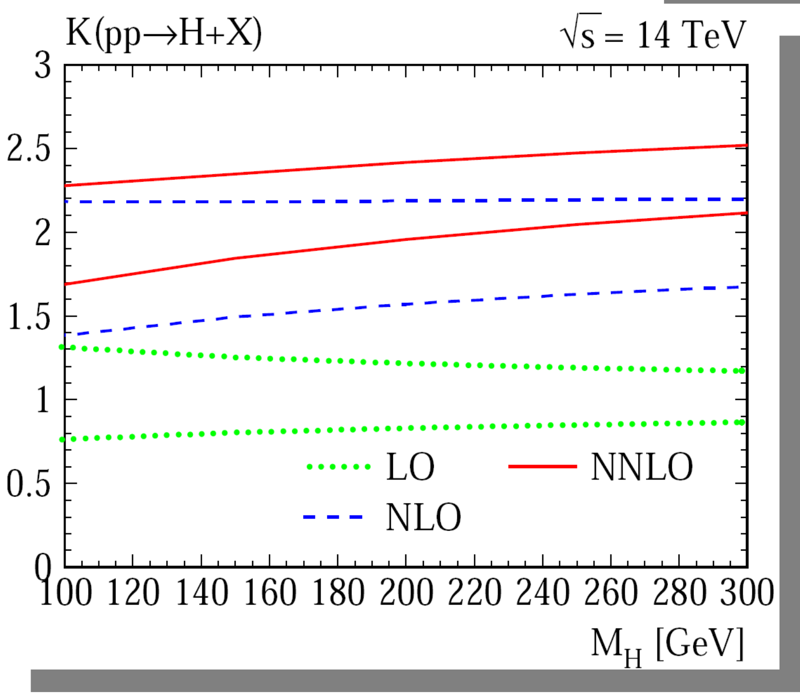
Boughezal, Czakon (2006)

Recent activities

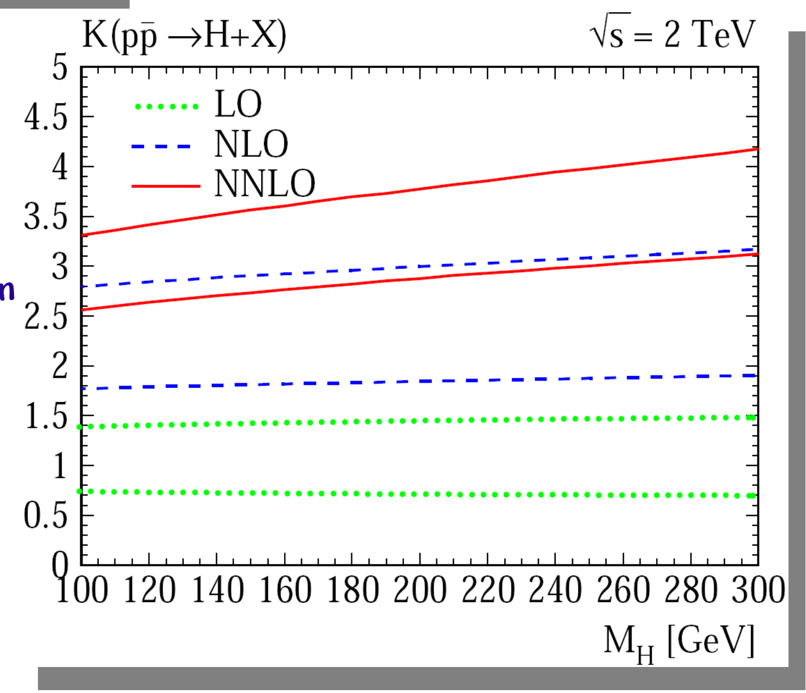
Higgs Physics: SM

What we have learned from QCD corrections to gg → H in the past:





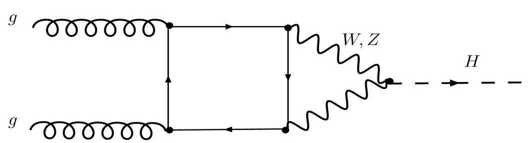
Harlander, Kilgore;
Anastasiou, Melnikov;
Ravindran, Smith, van Neerven
2002, 2003



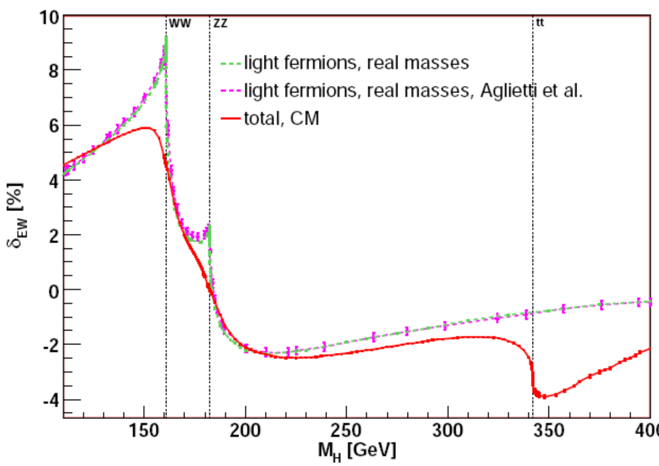
K-factor: roughly 2 at LHC, 3.5 at Tevatron

Electroweak Effects in Higgs Physics

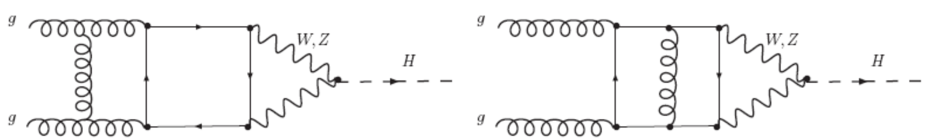
- Potentially large corrections to gg → H from EW effects; parametrically $y_{W,Z} N_F$
  No mF suppression for light fermions



Actis et al 2008



- what is the effect of QCD corrections to this contribution?



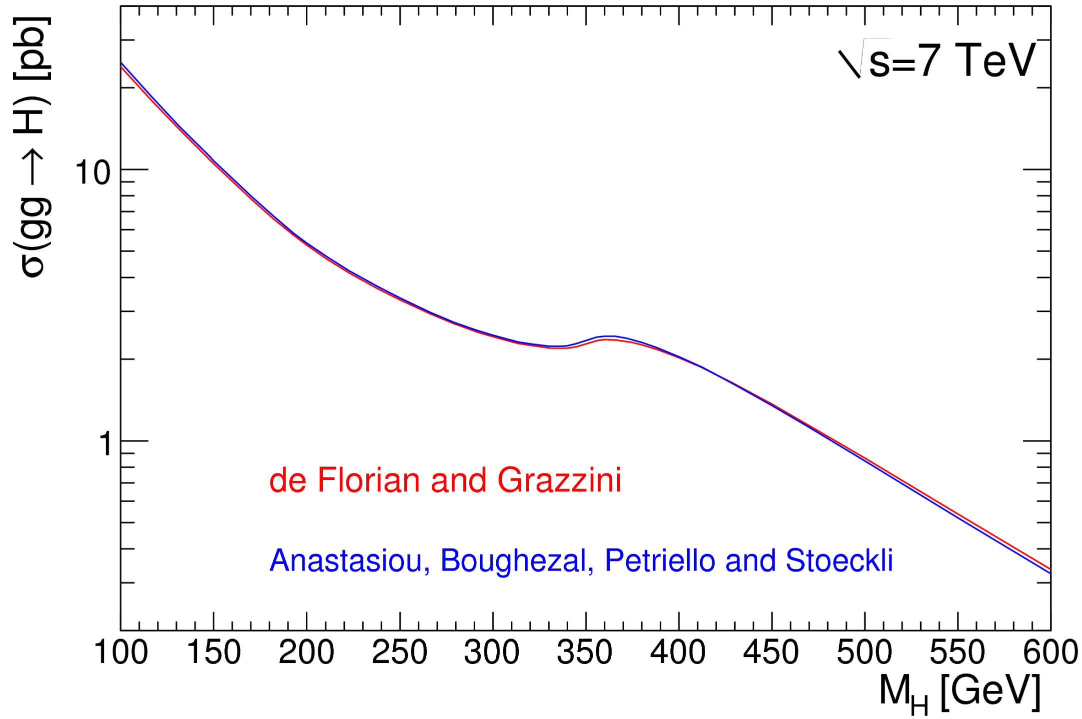
- No one knew! Requires 3loop multiscale calculation
- a K-factor between 1-3.5 was assumed in the literature
- Tevatron assumed a K-factor of 3.5 in their very first exclusion of SM mH= 170GeV
- Devised an EFT approach to estimate the K-factor; confirmed that 3.5 is correct
  Anastasiou, Boughezal, Petriello (2009)

Higgs Physics at the LHC: Argonne influence

- Provided the prediction for $gg \rightarrow H$ cross section at the Tevatron and LHC
- Our predictions are the official cross sections used by both colliders
- Results produced in collaboration with members of the theory group at Argonne

➡ This is a pure Argonne product

CERN Yellow Report 2011



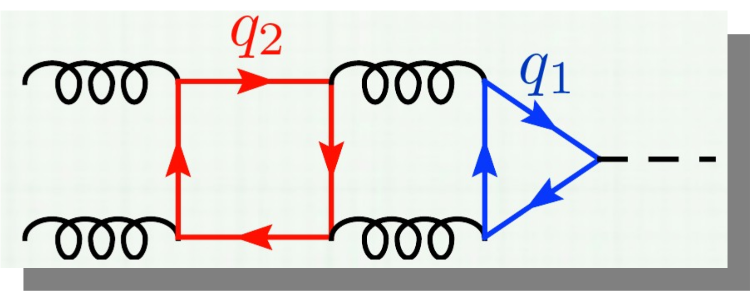
3) **Handbook of LHC Higgs Cross Sections: 1. Inclusive Observables.**
By LHC Higgs Cross Section Working Group (S. Dittmaier *et al.*). Jan 2011. 153pp. Temporary entry
e-Print: **arXiv:1101.0593** [hep-ph]

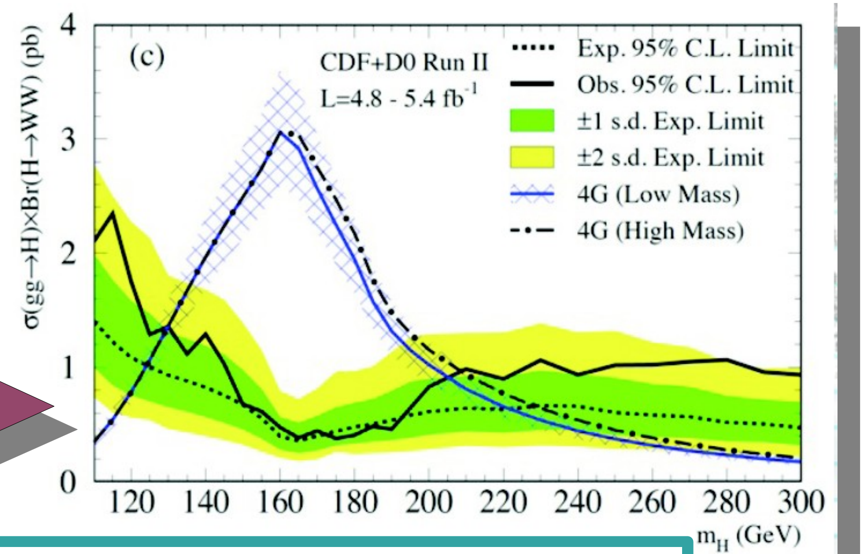
Higgs Physics: 4th Generation

- Quantified the effect of a fourth generation of heavy quarks on the Higgs Production cross section

- Result used by the Tevatron collaborations in their exclusions

Anastasiou, Boughezal, Furlan (2010)





$$\frac{\sigma(gg\to H)^{(n_h)}}{\sigma(gg\to H)^{(SM)}} = \frac{\Gamma(H\to gg)^{(n_h)}}{\Gamma(H\to gg)^{(SM)}} =$$

$$n_h^2 - \left(\frac{\alpha_s'(\mu)}{\pi}\right)^2 n_h \left[\frac{77}{288} n_h (n_h - 1) + \left(\frac{4}{3} n_l + \frac{19}{4}\right) \sum_q \log\left(\frac{m_q(\mu)}{m_t(\mu)}\right)\right] + \mathcal{O}(\alpha_s'^3)$$

New parametric effect at NNLO → breaks simple scaling mostly due to the n_h^3 term

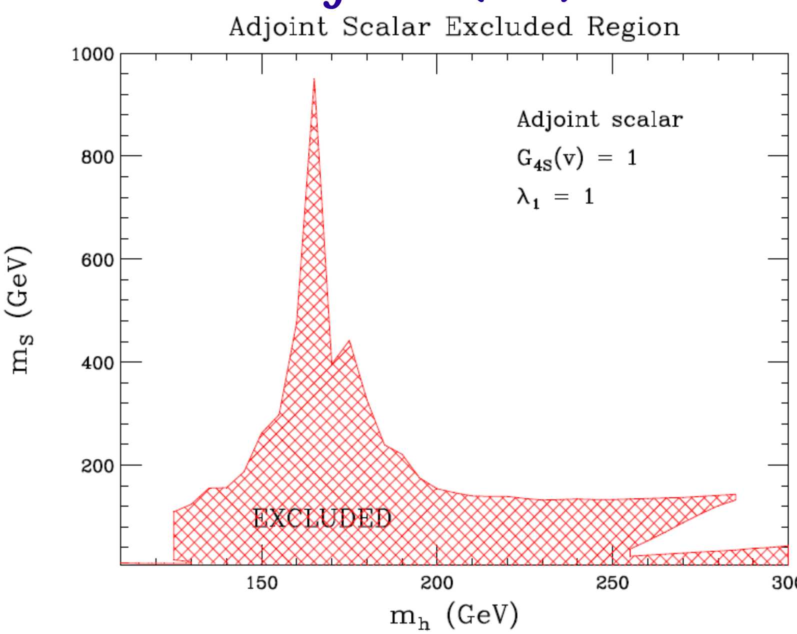
Higgs Physics: Colored Scalars

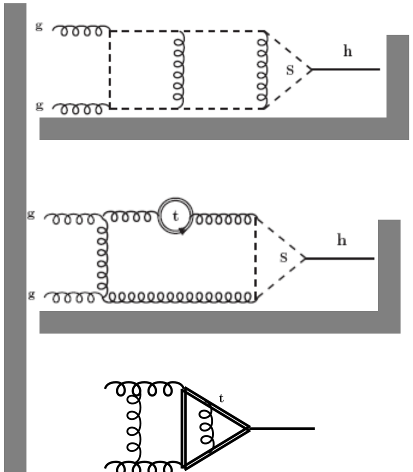
- Tevatron provided model independent bounds for gg → H → WW that can be used in learning about new physics

- I have Studied the effect of colored adjoint and fundamental scalar particles on the Higgs production cross section and used Tevatron bounds to constrain their parameter space

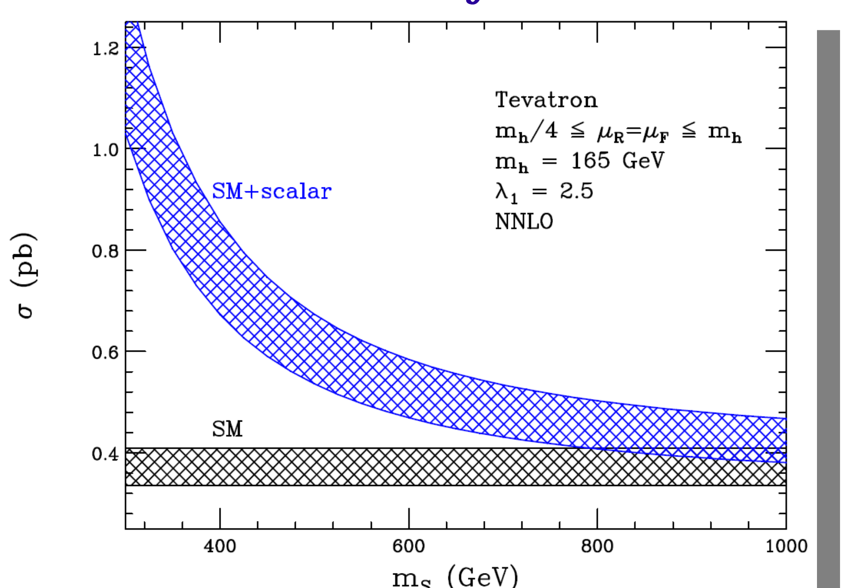
$$\mathcal{L}^{adj} = \mathcal{L}_{SM} + \mathrm{Tr}\left[D_\mu S D^\mu S\right] - m_S'^2\,\mathrm{Tr}\left[S^2\right] - g_s^2\, G_{4S}\,\mathrm{Tr}\left[S^2\right]^2 - \lambda_1 H^\dagger H\,\mathrm{Tr}\left[S^2\right],$$
$$\mathcal{L}^{fund} = \mathcal{L}_{SM} + \left(D_\mu S\right)^\dagger D^\mu S - m_S'^2\, S^\dagger S - \frac{1}{2} g_s^2\, G_{4S}\,\left(S^\dagger S\right)^2 - \lambda_1 H^\dagger H\, S^\dagger S.$$

Boughezal (2011)





Adjoint scalar Boughezal, Petriello (2010)



Hadronic-light-by-light contribution to the muon g-2

- The muon anomalous magnetic moment is one of the most precisely measured quantities in particle physics.

$$a_\mu^{\rm exp} = 11\ 659\ 2080(63) \times 10^{-11}$$

BNL measurement

- The theory prediction for this observable is highly developed:

$$a_\mu^{\rm th} = 11\ 659\ 1790(65) \times 10^{-11}$$

- Current discrepancy between theory and experiment is 3.2 sigma: is this a sign of new physics?

- a_μ obtained by combining QED, Electroweak and hadronic contributions

QED, Electroweak: under very good control

hadronic contributions: VP + hLBL

- Vacuum polarization (VP) estimated in a model independent way from e+e- → hadrons
- hLBL can not be directly related to experimental data and is model dependent.

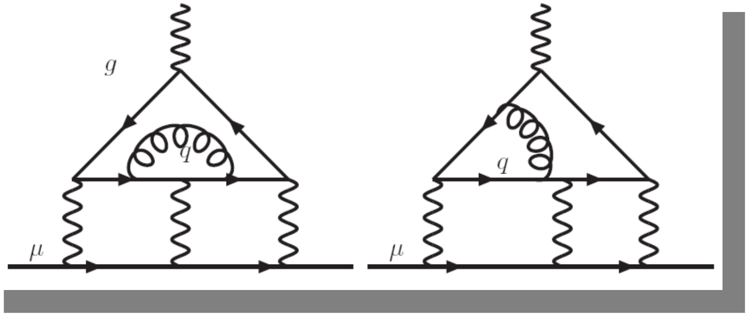
- Recent work claimed the hLBL contribution is enhanced over the current estimate by a factor of 2.

Hadronic-light-by-light contribution to the muon g-2

- We used the constituent quark loop to estimte the hLBL effects. The constituent quark masses are obtained by fitting them to the vacuum polarization result assuming that the same model correctly predicts the vacuum polarization.

- By deriving the NLO QCD correction to the constituent quark loop and the VP diagrams, we can check if the calculation of hLBL contribtion in the constituent quark model is robust.

LO: $$a_\mu^{\rm hlbl} = a_\mu^{\rm hvp}\,\frac{\alpha}{\pi}\left(\frac{3}{2}\zeta(3)-\frac{19}{16}\right)\frac{45\langle Q_q^4\rangle}{\langle Q_q^2\rangle}$$



- We found that the ratio was remarkably stable under QCD.

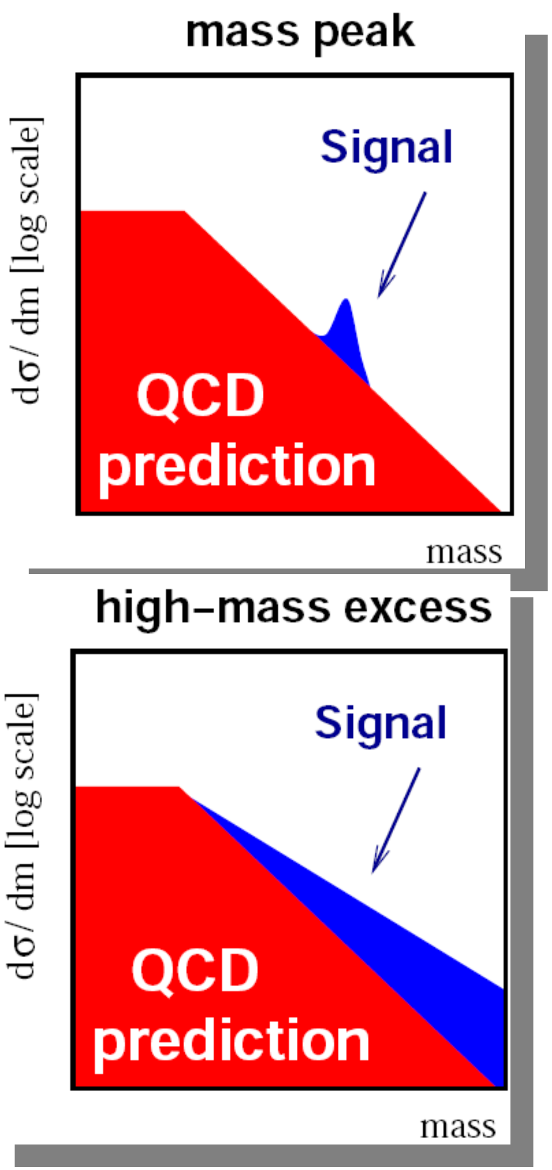
- Our results strengthen the 3 sigma discrepancy between theory and experiment
  Boughezal, Melnikov (2011)

Selected future work:

Double Real Radiation at NNLO
and the infrared problem

Collider Searches

G. Salam



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

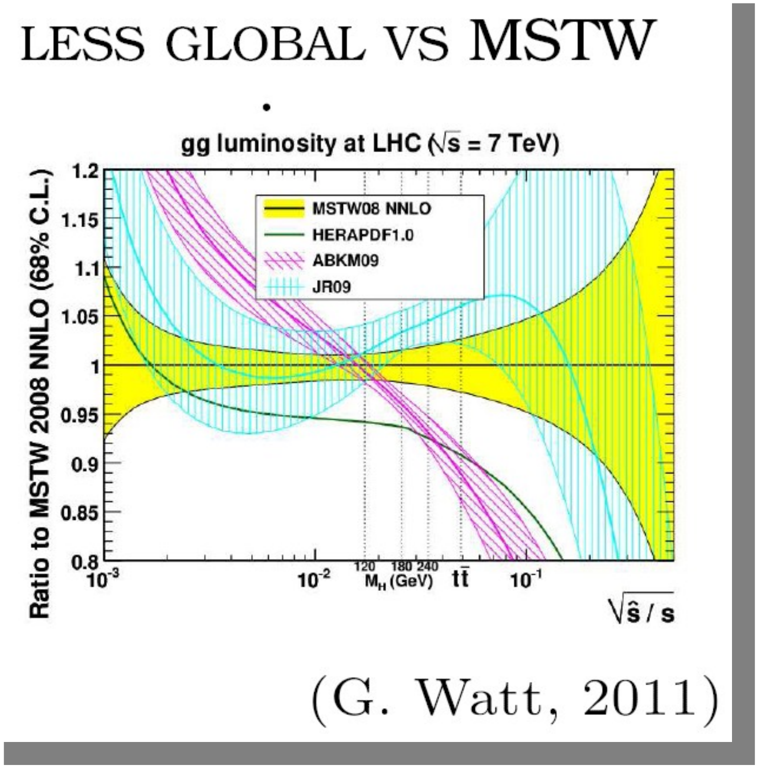
Examples: Higgs → WW , unreconstructed SUSY cascades

- Broad excess across many bins

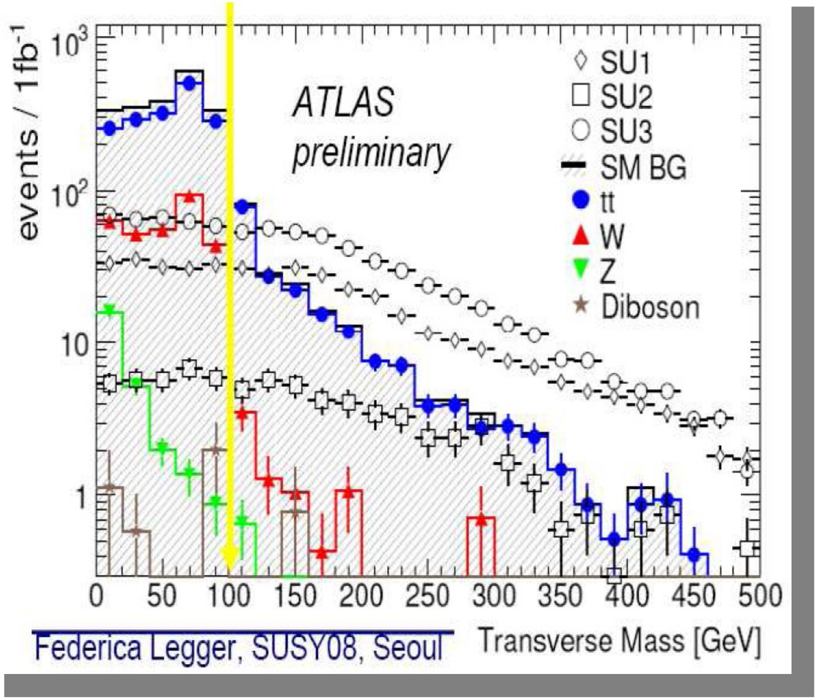
- Knowledge of background is crucial for discovery

Collider Searches

- Data = PDF x theory
  - MSTW high-x gluons comes from jet production
  - jet production is not known at NNLO !



- Susy searches require an understanding of the transverse mass shape

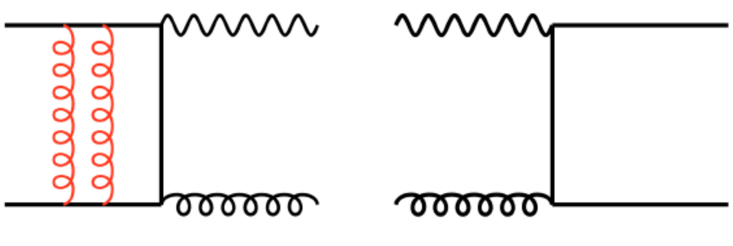


- NNLO QCD corrections are crucial for many observables to correctly describe/predict the shape of signals and backgrounds

The way to a differential NNLO MC program

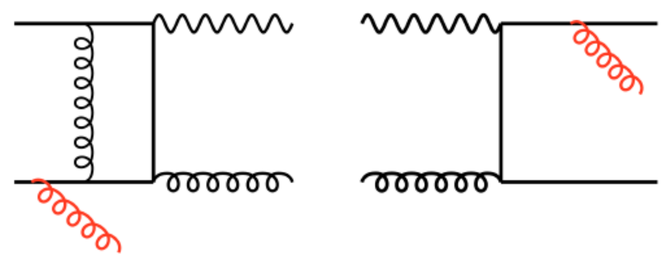
- What experimentalists need: fully differential numerical programs with NNLO precision that are flexible and allow to take into account complicated detector geometries and jet definitions.
- The ingredients needed to construct such NNLO programs (eg. V+jet):

2-loop matrix elements, m partons



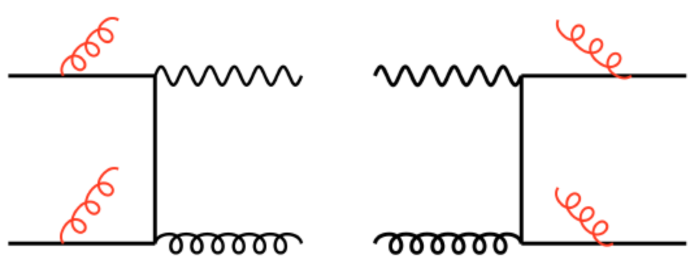
- **Explicit** IR poles from loop integrals

1-loop matrix elements, m+1 partons



- **Explicit** IR poles from loops
- **Implicit** IR poles from single unresolved radiation

Tree level matrix elements, m+2 partons



Implicit IR poles from double unresolved radiation

IR Safety

- An infrared safe observable forces us to integrate over the unresolved phase space to extract the implicit poles. A desirable way to do that is to integrate analytically.

Problem:

- differential cross sections require jet functions. Jet functions are functions that allow for arbitrary cuts on the phase space
- the presence of the jet function doesn't make it possible to integrate analytically

Solution: extract the IR singularities of the real radiation using IR subtraction terms.

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

Finite, can be integrated numerically

Integrated analytically

mass factorization Counter term

Subtraction @ NNLO

Structure of NNLO m-jet cross section:

$$
\begin{aligned}
\mathrm{d}\hat\sigma_{NNLO} = & \int_{\mathrm{d}\Phi_{m+2}} \left(\mathrm{d}\hat\sigma^{R}_{NNLO} - \mathrm{d}\hat\sigma^{S}_{NNLO}\right) + \int_{\mathrm{d}\Phi_{m+2}} \mathrm{d}\hat\sigma^{S}_{NNLO} \\
& + \int_{\mathrm{d}\Phi_{m+1}} \left(\mathrm{d}\hat\sigma^{V,1}_{NNLO} - \mathrm{d}\hat\sigma^{VS,1}_{NNLO}\right) + \int_{\mathrm{d}\Phi_{m+1}} \mathrm{d}\hat\sigma^{VS,1}_{NNLO} + \int_{\mathrm{d}\Phi_{m+1}} \mathrm{d}\hat\sigma^{MF,1}_{NNLO} \\
& + \int_{\mathrm{d}\Phi_{m}} \mathrm{d}\hat\sigma^{V,2}_{NNLO} + \int_{\mathrm{d}\Phi_{m}} \mathrm{d}\hat\sigma^{MF,2}_{NNLO}.
\end{aligned}
$$

$d\sigma^{S}_{NNLO}$: real radiation subtraction term for $d\sigma^{R}_{NNLO}$

$d\sigma^{VS,1}_{NNLO}$: One-loop virtual subtraction term for $d\sigma^{V,1}_{NNLO}$

$d\sigma^{V,2}_{NNLO}$: two-loop virtual corrections

Each of the differences above is finite and can be integrated numerically

Antenna Subtraction at NNLO

T. Gehrmann, A. Gehrmann, N. Glover (2005)

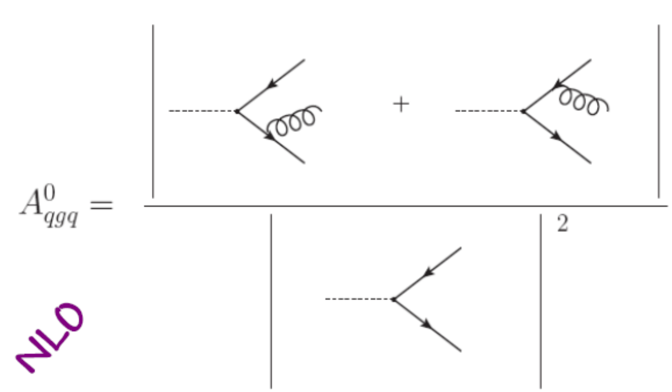
Antenna functions: derived from physical matrix elements normalized to two-parton matrix elements

$q\bar{q}$ from $\gamma \to q\,\bar{q}$

$q\,g$ from $\tilde{\chi} \to \tilde{g}\,g$

$g\,g$ from $H \to g\,g$

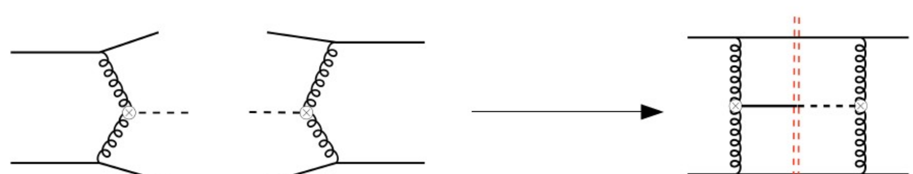
eg.



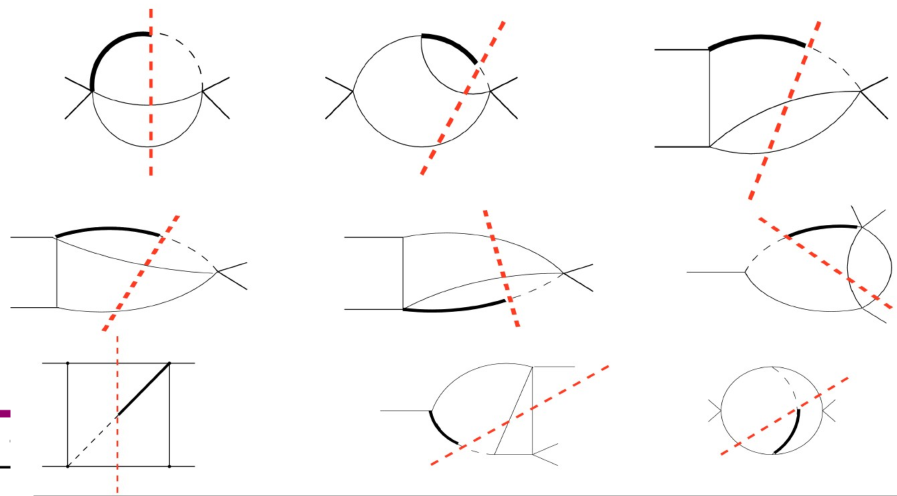
They refer to colour-ordered pairs of hard partons

$q\bar{q}$, $q\,g$, $g\,g$ with radiations in between

- At NNLO, there is a configuration where the unresolved partons are either soft or collinear to the initial state partons ⇒ needed for LHC processes
- It is not known how to deal with these singularities
- I have made a first step in extending this subtraction method to remove such singularities



Antenna Subtraction at NNLO



Boughezal, Gehrmann, Ritzmann (2010)

$$\mathcal{H}_{12} = -\frac{1}{\varepsilon}\left\{\frac{(x_1x_2+1)\left(\left(x_2^4+\left(x_1^2-4\right)x_2^2+1\right)x_1^2 \right.}{3\,(x_1+x_2)^4}\right.$$

$$\mathcal{H}_{13} = \frac{1}{\varepsilon^2}\left\{\frac{\left(x_1^2-2x_1+2\right)\left(x_2^2-2x_2+2\right)}{4\,x_1x_2}\right\}+\mathcal{O}\left(\frac{1}{\varepsilon}\right).$$

$$\begin{aligned}
\tilde{\mathcal{E}}_{12} = & \frac{1}{\varepsilon^3}\left\{\frac{\left(x_2^2-2x_2+2\right)\,\delta(1-x_1)}{4\,x_2}\right\} \\
& + \frac{1}{\varepsilon^2}\left\{-\frac{1}{2(x_1+1)\,x_2(x_1+x_2)^2}\left(-2x_1^2x_2^4-2x_1x_2^4-x_2^4+2x_1x_2^3\right.\right. \\
& \left. +2x_2^3+x_1^2x_2^2-2x_1x_2^2-2x_2^2-2x_1^2x_2+2x_1^2-4x_1x_2+4x_1\right) \\
& -\frac{\left(x_2^2-2x_2+2\right)\,\mathcal{D}_0(x_1)}{2x_2}+\delta(1-x_1)\left(\frac{\left(x_2^2-2x_2+2\right)\,H(-1,x_2)}{2x_2}\right. \\
& -\frac{\left(3x_2^2-6x_2+8\right)\,H(0,x_2)}{8x_2}+\frac{\left(x_2^2-2x_2+2\right)\,H(1,x_2)}{2x_2} \\
& \left.\left.-\frac{8\log(2)\,x_2^2-7x_2^2-16\log(2)\,x_2+24x_2+16\log(2)\,-20}{16x_2}\right)\right\}+\mathcal{O}\left(\frac{1}{\varepsilon}\right), \\
\tilde{\mathcal{E}}_{14} = & \frac{1}{\varepsilon^2}\left\{\delta(1-x_1)\left(\frac{(x_2+1)H(0,x_2)}{2}-\frac{(x_2-1)\left(4x_2^2+7x_2+4\right)}{12x_2}\right)\right\}+\mathcal{O}\left(\frac{1}{\varepsilon}\right) \\
\tilde{\mathcal{E}}_{23} = & \frac{1}{\varepsilon^2}\left\{\frac{x_1x_2(x_1x_2+1)^2\left(x_1^2+x_2^2-2\right)}{(x_1+x_2)^4}\right\}+\mathcal{O}\left(\frac{1}{\varepsilon}\right), \\
\tilde{\mathcal{E}}_{24} = & \frac{1}{\varepsilon}\left\{-\frac{1}{6x_1^3(x_1+x_2)^3}\left[(x_2-1)\left(12x_1^9+36x_2x_1^8-6x_1^8+41x_2^2x_1^7-19x_2x_1^7\right.\right.\right. \\
& -x_1^7+19x_2^3x_1^6-29x_2^2x_1^6-5x_2x_1^6+4x_2^4x_1^5-20x_2^3x_1^5-26x_2^2x_1^5+15x_2x_1^5 \\
& -6x_2^4x_1^4-30x_2^3x_1^4+73x_2^2x_1^4+10x_2x_1^4-2x_1^4-12x_2^4x_1^3+86x_2^3x_1^3+50x_2^2x_1^3 \\
& \left.\left.-34x_2x_1^3+32x_2^4x_1^2+62x_2^3x_1^2-118x_2^2x_1^2+24x_2^4x_1-132x_2^3x_1-48x_2^4\right)\right] \\
& +\frac{\left(2x_1^8+x_2x_1^7-x_1^6+2x_2^2x_1^4-x_2x_1^3-8x_2^2x_1^2+2x_2x_1+8x_2^2\right)}{x_1^4}\times \\
& \left.(G(-x_2,x_1)-H(-1,x_1))+x_1^2\left(2x_1^2+x_1x_2-1\right)H(0,x_2)\right\}+\mathcal{O}(1).
\end{aligned}$$

$$\begin{aligned}
\mathcal{B}_{12} = & -\frac{1}{\varepsilon^3}\left\{\frac{\delta(1-x_1)\,\delta(1-x_2)}{12}\right\} \\
& +\frac{1}{\varepsilon^2}\left\{\delta(1-x_1)\left(-\frac{1+x_2}{12}+\frac{1}{6}\mathcal{D}_0(x_2)-\frac{5}{36}\delta(1-x_2)\right)\right. \\
& \left.+\left(\frac{1}{6}\mathcal{D}_0(x_1)-\frac{1+x_1}{12}\right)\delta(1-x_2)\right\}+\mathcal{O}\left(\frac{1}{\varepsilon}\right), \\
\mathcal{B}_{13} = & \frac{1}{\varepsilon^2}\delta(1-x_1)\left\{\frac{(1-x_2)(4x_2^2+7x_2+4)}{24x_2}+\frac{1+x_2}{4}H(0,x_2)\right\} \\
& +\mathcal{O}\left(\frac{1}{\varepsilon}\right).
\end{aligned}$$

Derivation of the remaining antennae is in progress

A numerical Method for the IR Problem at NNLO

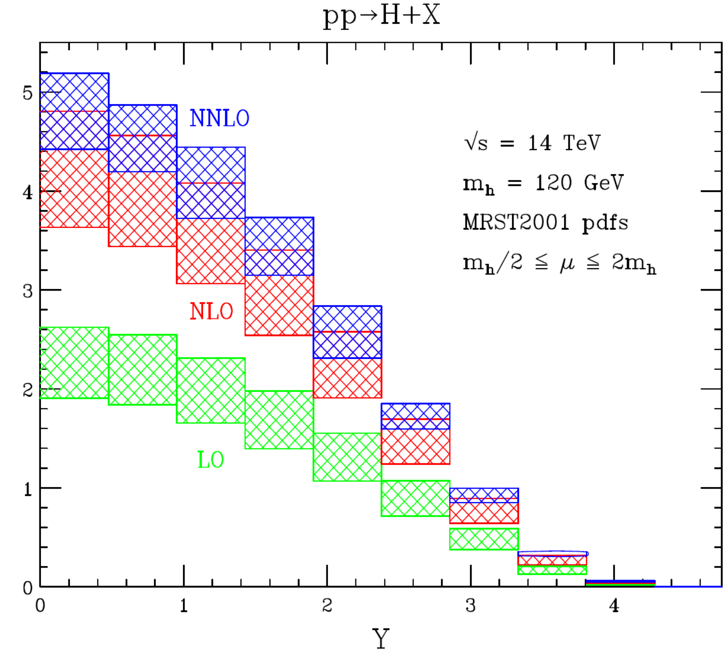
- The infrared problem at NNLO is an uncharted territory; study of multiple approaches is important at this stage

- A technique based on sector decomposition was successful in the past in providing predicitions   Anastasiou, Melnikov, Petriello (2003)

$$I = \int_0^1 \mathrm{d}x\,\mathrm{d}y\, x^{-1-\epsilon} y^{-1-\epsilon} (x+y)^{-\epsilon}$$

$$I_1 = \int_0^1 \mathrm{d}x \int_0^x \mathrm{d}y\, x^{-1-\epsilon} y^{-1-\epsilon} (x+y)^{-\epsilon}, \quad I_2 = \int_0^1 \mathrm{d}y \int_0^y \mathrm{d}x\, x^{-1-\epsilon} y^{-1-\epsilon} (x+y)^{-\epsilon}$$

$$I_1 = \int_0^1 \mathrm{d}x\,\mathrm{d}y\, x^{-1-3\epsilon} y^{-1-\epsilon} (1+y)^{-\epsilon}, \quad I_2 = \int_0^1 \mathrm{d}x\,\mathrm{d}y\, y^{-1-3\epsilon} x^{-1-\epsilon} (1+x)^{-\epsilon}$$

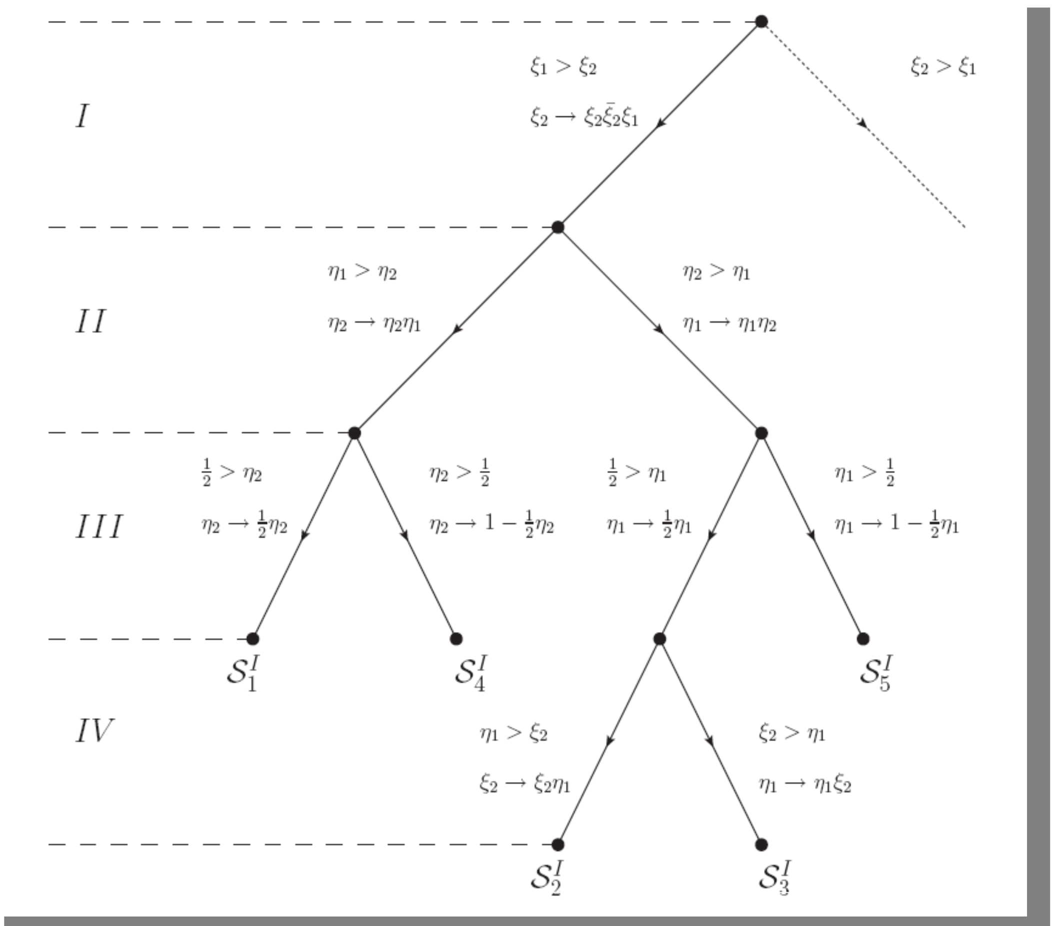


Anastasiou, Melnikov, Petriello (2004)

A Numerical Method for the IR Problem at NNLO

- The method in its original version was process dependent → very tedious work is required from scratch for each new process

- Recent work has suggested how to remove this limitation Czakon (2010)



- applies to any process upon suitable partitioning of the phase space

- potentially a breakthrough in this field, but many issues are not yet understood

First Physics Applications

- Heavy particles decays: $O(\alpha^2)$ Corrections to $W \to l\,\nu$

W Boson Mass Fit Uncertainties (MeV) from CDF

(CDF, PRL 99:151801, 2007; Phys. Rev. D 77:112001, 2008)

	electrons	muons	common
W statistics	48	54	0
Lepton energy scale	30	17	17
Lepton resolution	9	3	-3
Recoil energy scale	9	9	9
Recoil energy resolution	7	7	7
Selection bias	3	1	0
Lepton removal	8	5	5
Backgrounds	8	9	0
production dynamics	3	3	3
Parton dist. Functions	11	11	11
QED rad. Corrections	11	12	11
Total systematic	39	27	26
Total	62	60	

Theory uncertainty

Kotwal, LoopFest 2011

- won't get the anticipated precision at LHC without this NNLO calculation

$$\delta M_W = 5 - 10\ MeV$$

- work in progress using the sectors technique

First Physics Applications

- Heavy particles decays: top → W b → l nu b

  - millions of top quarks at LHC → need a realistic description of them including differential decays

  - what is the effect of cuts on the top properties ?

  - does the top have a right handed coupling component ?

  - need SM predictions at NNLO in order not to confuse SM effects with new physics

  - this is an extension of the previous project and similar ideas are applied

Long term plans

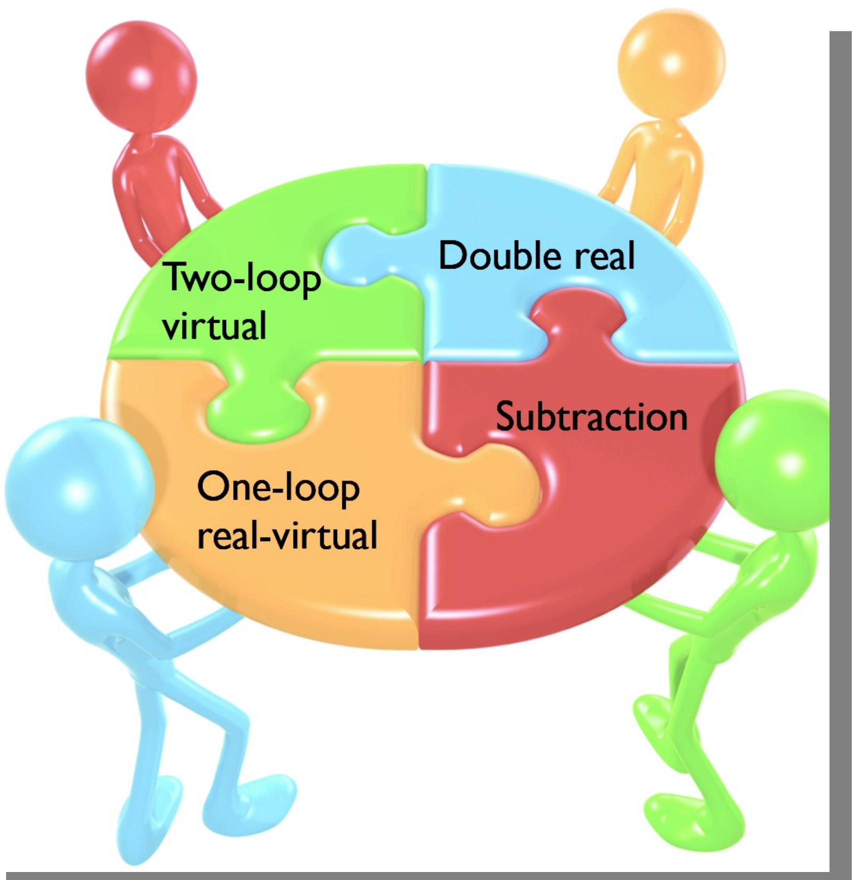
- In the long term, many other processes will be studied, eg. $pp \to W/Z$+jets, $pp \to 2$jets, ...

- Aim: provide the predictions in the form of simulation codes that allow for arbitrary cuts following the experimental needs

Long term plans

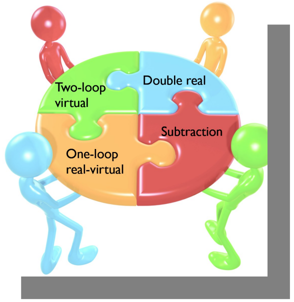
- In the long term, many other processes will be studied, eg. pp $\to$ W/Z+jets, pp $\to$ 2jets, ...

- Aim: provide the predictions in the form of simulation codes that allow for arbitrary cuts following the experimental needs



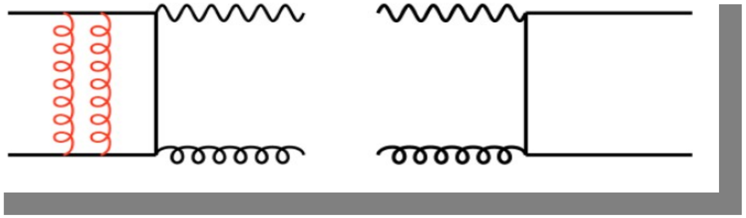
The ingredients for NNLO cross sections

Long term plans

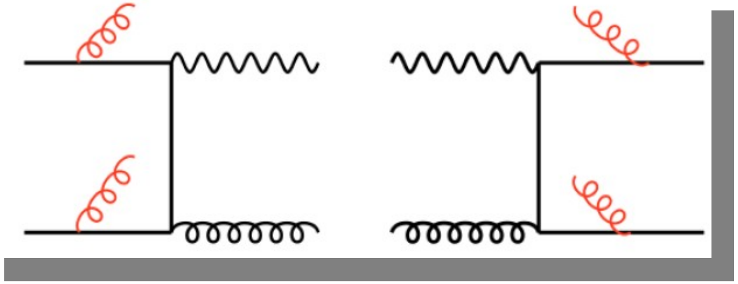


- In the long term, many other processes will be studied, eg. pp $\to$ W/Z+jets, pp $\to$2jets, ...

- Aim: provide the predictions in the form of simulation codes that allow for arbitrary cuts following the experimental needs

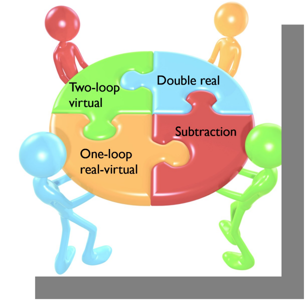


I have the expertise to provide missing pieces



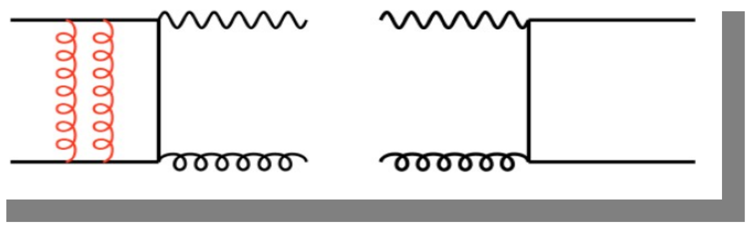
Working on subtraction schemes
to remove the IR divergencies
in collaboration with F. Petriello

Long term plans

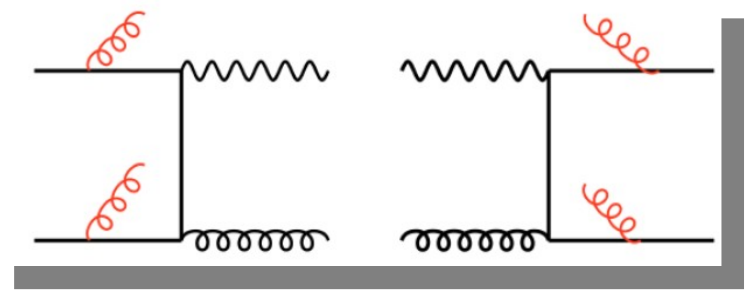


- In the long term, many other processes will be studied, eg. pp → W/Z+jets, pp → 2jets, ...

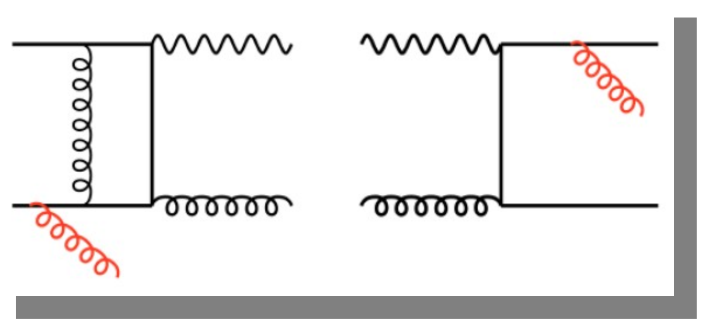
- Aim: provide the predictions in the form of simulation codes that allow for arbitrary cuts following the experimental needs



I have the expertise to provide missing pieces



Working on subtraction schemes
to remove the IR divergencies
in collaboration with F. Petriello



M. Schulze, Argonne Director Fellow
expert on one-loop calculations
joining us this September

Summary of my activities: 2010-2011

Invited and plenary talks:

-Anual German Physical Society meeting 2010
- DIS 2010
- Planck 2010
- LoopFest 2010
- DIS 2011
- Implications of Electroweak Symmetry Breaking, workshop in Madison (2011)

Seminars:

- Durham, Madison, Argonne, Northwestern, Fermilab, SLAC, Johns Hopkins

Organized Conferences:

RadCor: co-organizer and co-editor (Switzerland)
LoopFest 2011: co-organizer, jointly organized by Argonne and Northwestern

Upcoming:

- Physics at LHC 2011, Perugia, Italy, invited review on higher order calculations
- DPF 2011, invited review on Higgs physics

Summary of my activities: 2010-2011

- Refereed Papers:

- Hadronic light-by-light scattering contribution to the muon magnetic anomaly: constituent quark loops and QCD effects,
  R. Boughezal, K. Melnikov, arXiv:1104.4510 [hep-ph]
- Constraints on heavy colored scalars from Tevatron's Higgs exclusion limit.
  R. Boughezal, Phys.Rev.D83:093003,2011
- Antenna subtraction at NNLO with hadronic initial states: double real radiation for initial-initial configurations with two quark flavours
  R. Boughezal, A. Gehrmann-De Ridder, M. Ritzmann, JHEP 1102:098,2011
- The NNLO gluon fusion Higgs production cross-section with many heavy quarks
  C. Anastasiou , R. Boughezal, E. Furlan, JHEP 1006:101,2010.
- Color-octet scalar effects on Higgs boson production in gluon fusion
  R. Boughezal, F. Petriello, Phys.Rev.D81:114033,2010

- CERN Yellow Report

Handbook of LHC Higgs Cross Sections: 1. Inclusive Observables.
By LHC Higgs Cross Section Working Group (S. Dittmaier et al.). Jan 2011. 153pp

- Conference Proceedings:

- Antenna subtraction for two hadronic initial states at NNLO
  R. Boughezal, A. Gehrmann-De Ridder, M. Ritzmann, PoS DIS2010:101,2010
- Precise predictions for Higgs production in models with color-octet scalars
  R. Boughezal, F. Petriello, Nucl.Phys.Proc.Suppl.205-206:289-294,2010
- NNLO antenna subtraction with two hadronic initial states
  R. Boughezal, A. Gehrmann-De Ridder, M. Ritzmann; PoS RADCOR2009:052, 2010
- The SM and NLO Multileg Working Group: Summary report.
  By SM and NLO Multileg Working Group (J.R. Andersen et al.). Mar 2010. 169pp

Summary

- Many ambitious plans for the future with direct impact on the experimental program and lot of exciting work to do

- Lab has supported this program in the form of personnel with the director's fellow

- We strongly hope that the DOE will be supportive