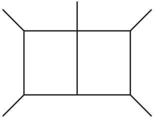
# Physics at Hadron Colliders

## Precision QCD at High Energies



Fernando Febres Cordero
Department of Physics, University of Freiburg

SILAFAE

Antigua, Guatemala, November 2016

ALBERT-LUDWIGS-UNIVERSITÄT FREIBURG

Alexander von Humboldt Stiftung/Foundation

# Outline

## GREAT ACHIEVEMENTS @ LHC
Higgs, Complex signals, Complete SM, Beyond the SM?

## SEARCHES FOR NEW PHYSICS
Bump hunting, Distribution excesses, Precision

## THE QUEST FOR 1% QCD
The NNLO revolution, Th uncertainties, High multiplicities

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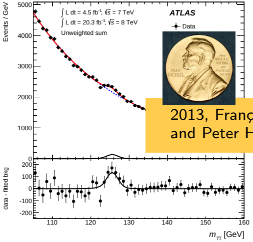
# A Complete Standard Model of Particle Physics

The SM is a quantum field theory that describes fundamental matter and their (strong and EW) interactions

- With the discovery of the Higgs Boson at the LHC in 2012, the last missing piece of the SM has been found
- We can now directly constraint all 19 parameters of the model




2013, François Englert and Peter Higgs

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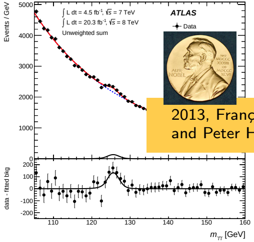


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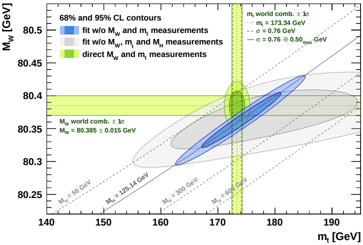
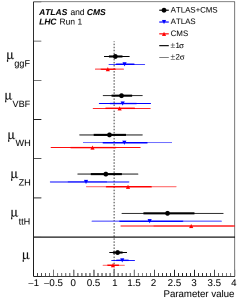
- Global fits of observables can now be achieved, and theory/experiment comparisons can hint for problems with the SM
- The example figure shows a multidimensional fit by the `Gfitter` collaboration on the observables $M_W$, $m_t$ and $M_H$



# Higgs Phenomenology - LHC Run I

arXiv:1606.02266 [hep-ex]

- Signal strengths for production mechanisms
- Includes *gluon fusion*, *VBF*, *Higgsstrahlung* and $t\bar{t}H$
- ATLAS, CMS and combined results shown



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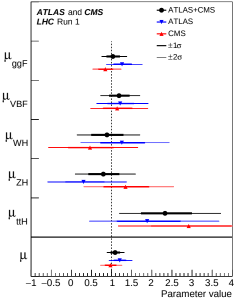
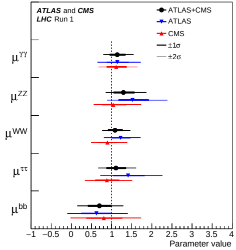



- Signal strengths for decay processes
- Shown are Higgs decaying into pairs of vector bosons and to fermion pairs
- Excellent overall agreement, though large uncertainties



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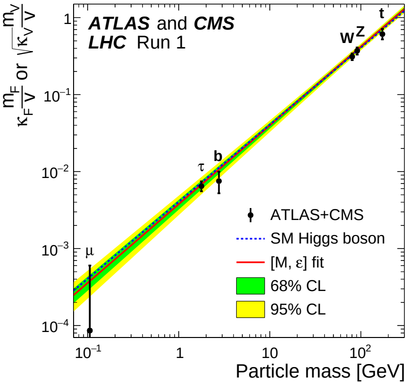
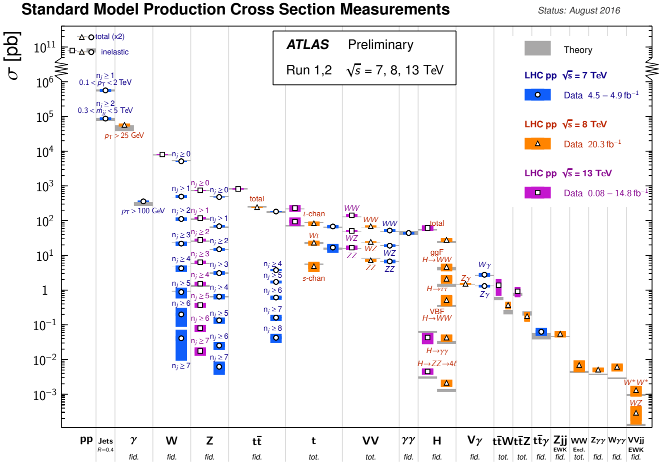



The coupling strength of the Higgs boson to weak bosons (sqrt) and fermions as a function of the particle mass.
A *qualitative* compatibility to SM predictions is observed

# SM Cross Sections at ATLAS




- Many processes studied
- Overall (impressive) th/ex agreement
- Jet towers deeply testing QCD
- Smallest xs's from $VV' + 2$ jets
- Similar results from CMS

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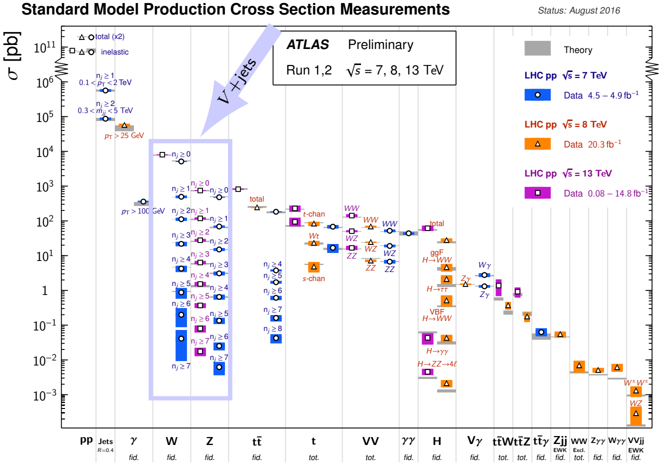


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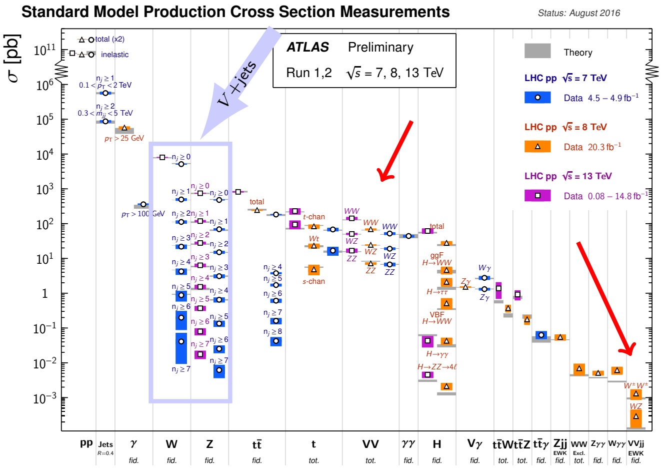


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## A Tale of Troublesome Success

# The Shortcomings of the SM

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- Can we understand the structure of the SM symmetry group and its matter content?
- Why the mass hierarchies in the fermion sector and other peculiarities of its parameters?
- Why the hierarchy between the *electroweak* scale and the *Planck* scale?

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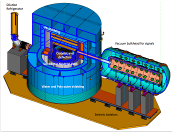
- Can we consistently include gravity within the SM?

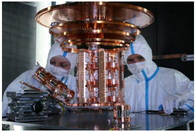
Many Beyond the SM models have been proposed through the years to deal with some of these problems: *Supersymmetry, Extra dimensions, Composite Theories, Strings, Axions, Extra fields, etc.*

# Searching for Answers: Dark Matter Experiments

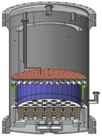
SuperCDMS: a cryogenic dark matter search experiment, located at SNOLAB, Ontario, Canada




CRESST: a cryogenic superconducting thermal dark matter experiment, located at Gran Sasso, Italy



PandaX: a xenon based dark matter search experiment, located at CJPL, Sichuan, China



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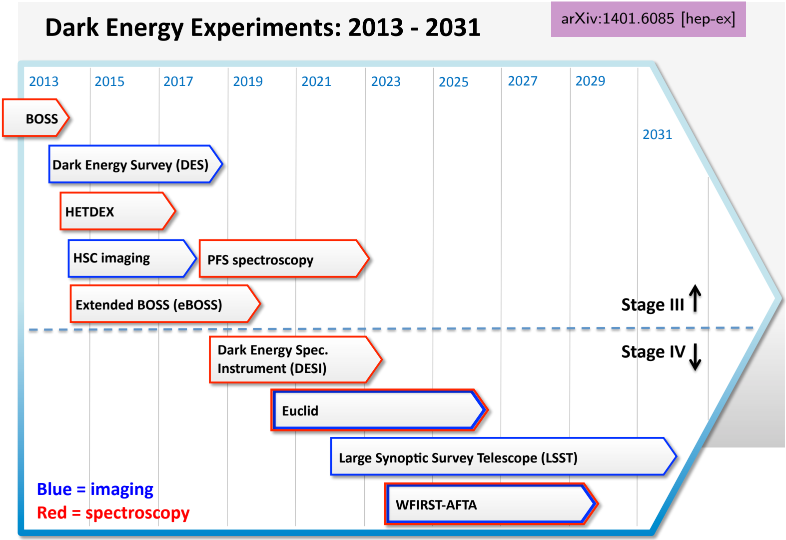
# Searching for Answers: Dark Energy Surveys



# Searching for Answers with Collider Experiments

LHC: proton-proton collider up to a design energy of $14$ TeV, CERN, Geneva

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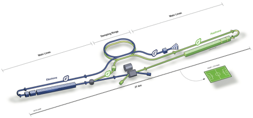
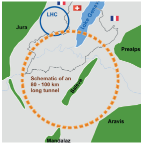
ILC: proposed Int. Linear Collider (0.5-1 TeV) with possible hosts Japan, Europe or the USA



FCC-CEPC: proposed future circular colliders to reach $\sim 100$ TeV in energy, possibly at CERN and China



# Searches at Hadron Colliders

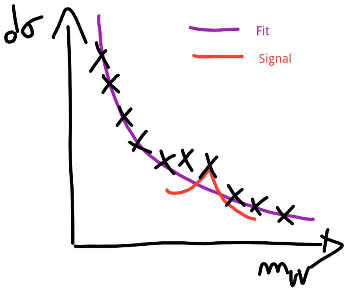
Clear New Signals

vs.

New Signal Excesses

# Bumps and Excesses at Colliders

When a heavy state is produced, that couples to SM particles, there is the possibility of a discovery by characterizing a *peak* on a related observable. Detection depends on the relative size of the signal and backgrounds



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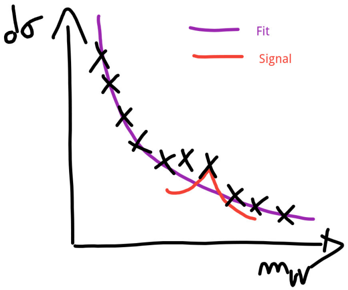


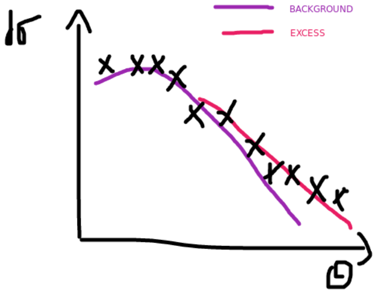


Unlike resonance signals, there are many BSM scenarios that enhance certain observables in a smooth way. In these cases a precise knowledge of the background is necessary

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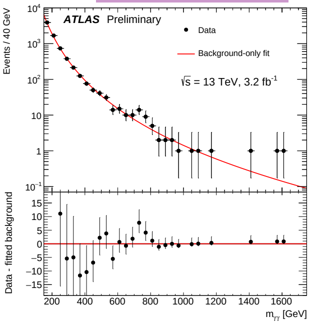
# The Brief Story of a Diphoton Resonance

ATLAS-CONF-2015-081

- On Dec. 15, 2015 the ATLAS and CMS collaboration reported on first results from Run II at $\sqrt{s} = 13$ TeV
- Both collaboration saw a curious excess of *diphoton* events at around $M_{\gamma\gamma} = 750$ GeV
- The statistical significance of the deviations was above 3 sigmas



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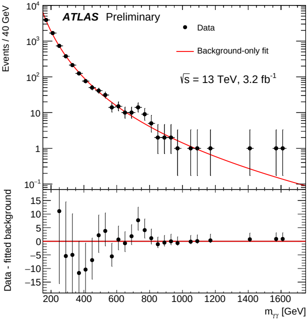
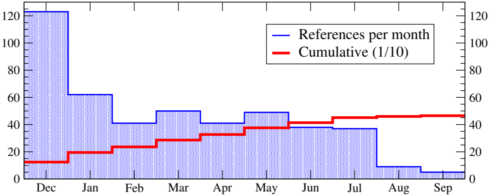
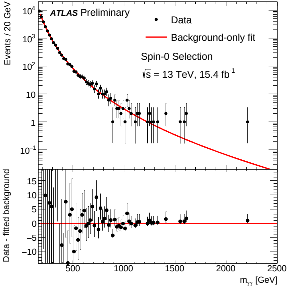


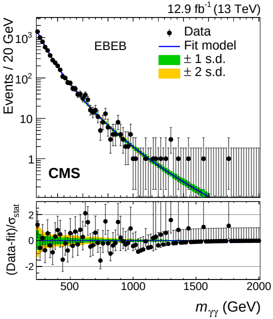




- An avalanche of attention followed
- More than 400 articles explored in different ways the deviation

# August Dismissal of a Fluctuation

But in Aug. 5, 2016 both collaborations revisited the measurement with more than 4 times the amount of data



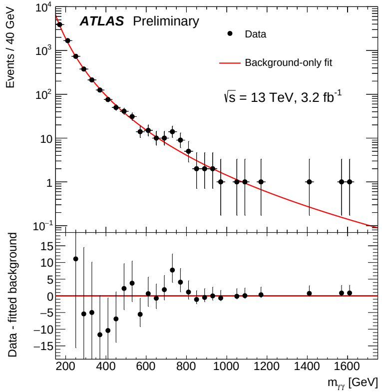

- The *evidence* of a resonance observed earlier was deemed a fluctuation of the background
- No matter how big data sets are, always in tails of distributions fake excesses can appear

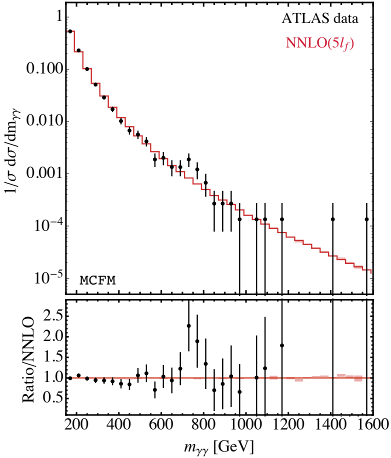
# Few Comments on the Experience

- Clear signatures are simplest to analyze, though dataset size important
- Eager community to find hints of BSM
- Precision Calculations are keen even for clear signatures, both to cross check experimental fits techniques and for finding $\mathcal{O}(1-5\%)$ effects

# The $M_{\gamma\gamma}$ Spectrum at NNLO QCD

With a precise calculation by Campbell, Ellis, Li and Williams the experimental fits were validated



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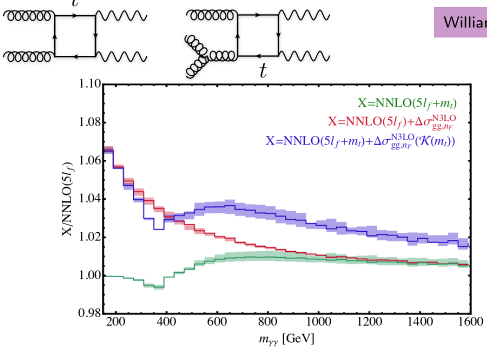
Predictions at high invariant masses.

As we all know, bump hunts in the diphoton system assume a smooth function which can be fitted to the data. Begging the question,

How smooth is smooth? :-)

Williams at Moriond 2016



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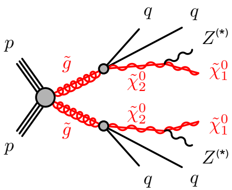
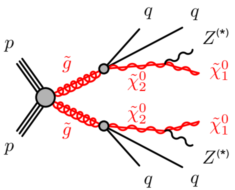
# Excesses in SUSY Searches




- As an example, in many SUSY models heavy colored particles are pair produced
- They produce long decay chains of jets and leptons
- In the end heavy neutral stable particles scape the detector, producing missing energy

# Excesses in SUSY Searches

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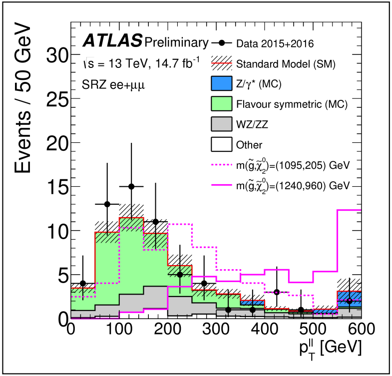
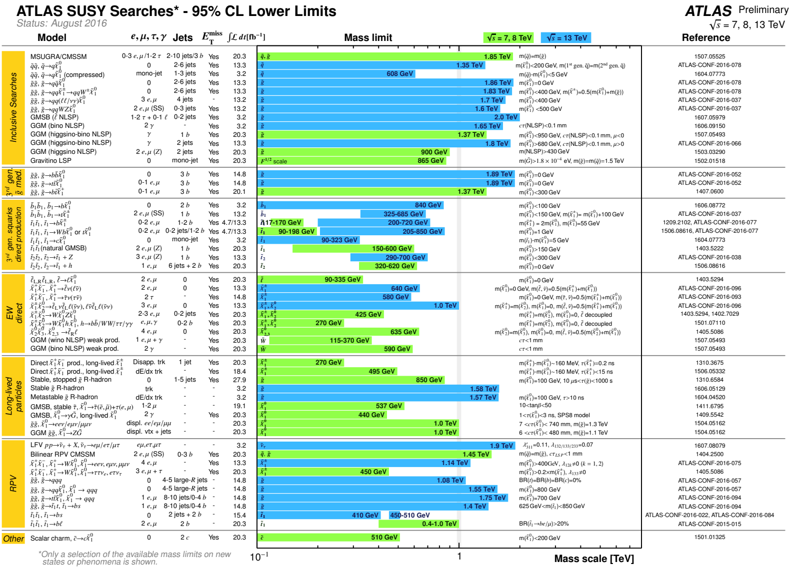


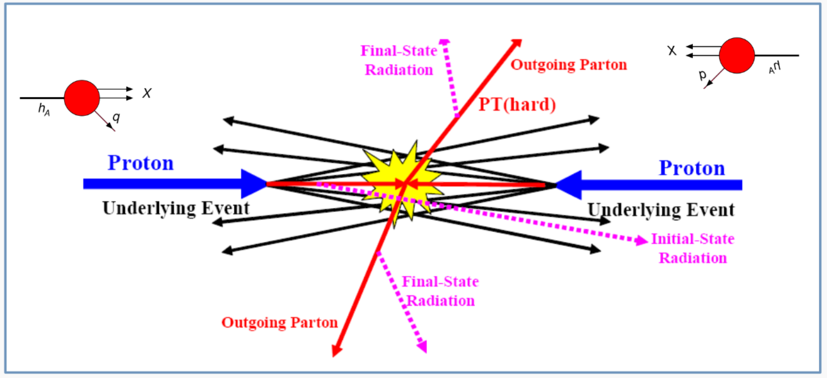

$p_{\mathrm{T}}^{ll}$ is one of the employed observables, with possible NP modifying the associated distributions

# Summary Plots for SUSY Exclusion Limits



## QCD for Precise Hadron Collider Phenomenology

# The Anatomy of Hadron-Hadron Collisions




- Hadron colliders are messy environments
- Access to high-energy interactions occurs in head on collisions and are described by so called partonic hard cross sections
- Radiation from incoming and outgoing partons always present
- Also soft physics related to the Underlying events, among other low-energy effects

# Partonic Cross Section in Perturbation Theory

$$\hat{\sigma}(\alpha_s, \mu_F, \mu_R) = [\alpha_s(\mu_R)]^{n_\alpha}\left[\hat{\sigma}^{(0)} + \frac{\alpha_s}{2\pi}\hat{\sigma}^{(1)}(\mu_F,\mu_R) + \left(\frac{\alpha_s}{2\pi}\right)^2 \hat{\sigma}^{(2)}(\mu_F,\mu_R) + \cdots\right]$$

LO NLO NNLO

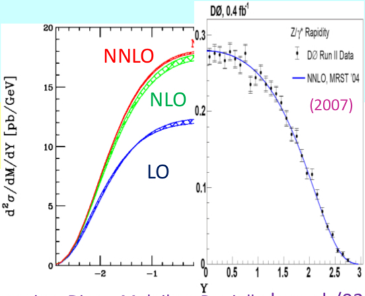
from L. Dixon

**Problem:** Leading-order, tree-level predictions only qualitative due to **poor convergence** of expansion in $\alpha_s(\mu)$ (setting $\mu_R = \mu_F = \mu$ )

Example: *Z* production at Tevatron
Distribution in rapidity *Y*

$$Y = \frac{1}{2}\ln\left(\frac{E + p_z}{E - p_z}\right)$$

$\frac{d\sigma}{dY}$ has $n_\alpha = 0$




still ~50% corrections, LO → NLO

[Anastasiou, Dixon, Melnikov, Petriello hep-ph/0312266]

# Quantum Corrections in QCD

Goal:

- Increased accuracy (expansion in small coupling constant)

Issues:

- Analytic complexity
- Numerical computing time for phase space integrations

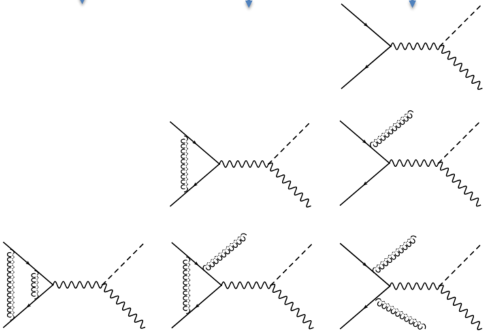
$$d\sigma^{NNLO} = \alpha_S^{\,n}(m_{tree} + \alpha_S m_{1\text{-}loop} + \alpha_S^{\,2} m_{2\text{-}loop})$$
$$= \alpha_S^{\,n}(\tilde{m}_{tree} + \alpha_S \tilde{m}_{1\text{-}loop} + \alpha_S^{\,2} \tilde{m}_{2\text{-}loop})$$

Two-Loop | One-Loop | Tree-Level

LO ($O(\alpha_S^{\,n})$) →

NLO (adds $O(\alpha_S^{\,n+1})$) →

NNLO (adds $O(\alpha_S^{\,n+2})$) →

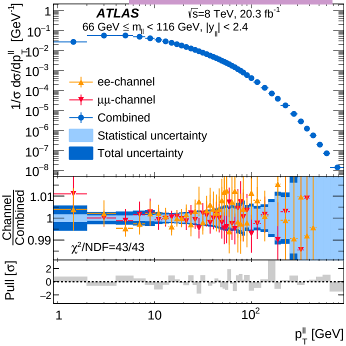


W. Giele

# The $\sim 1\%$ Frontier at the LHC

- $p_T^{ll}$ in Drell-Yan, an impressive example of precise differential measurements by ATLAS
- By normalizing to inclusive $Z$ cross section, improvement in uncertainties
- Total uncertainties below $1\%$ for $p_T^{ll} < 200$ GeV

arXiv:1512.02192 [hep-ex]



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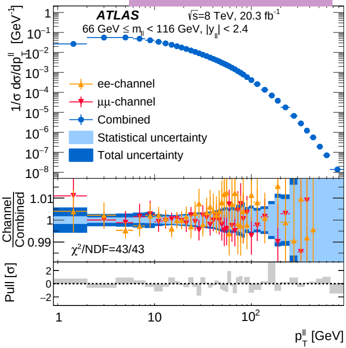
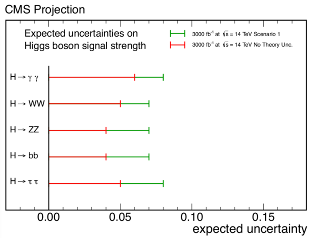
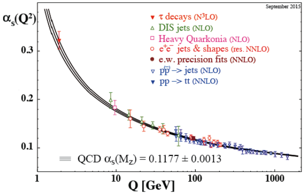


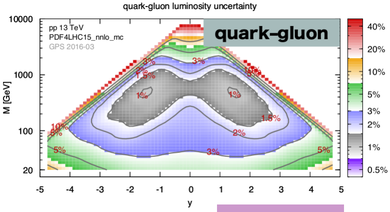

- Higgs phenomenology will benefit also from high luminosity runs
- Signal strength relative errors could reach few percent
- Recent theoretical advances would allow matching this precision



# Ingredients for QCD at $\sim 1\%$

In order to compute quantum QCD corrections two fundamental inputs are required: the strong coupling $\alpha_s$ and the *Parton Distribution Functions*




From G. Salam

- Naively one is to expect NLO QCD corrections to be of order $\sim 10\%$ and NNLO QCD at $\sim 1\%$
- Perturbative calculations are also required for the partonic cross sections associated to the signal studied

# State-of-the-Art QCD Phenomenology

| | | | |
|---|---|---|---|
| dijets | O(3%) | gluon-gluon, gluon-quark | PDFs, strong couplings, BSM |
| H+0 jet | O(3-5 %) | fully inclusive (N3LO ) | Higgs couplings |
| H+1 jet | O(7%) | fully exclusive; Higgs decays, infinite mass tops | Higgs couplings, Higgs $p_t$, structure for the ggH vertex. |
| tT pair | O(4%) | fully exclusive, stable tops | top cross section, mass, $p_t$, FB asymmetry, PDFs, BSM |
| single top | O(1%) | fully exclusive, stable tops, t-channel | $V_{tb}$, width, PDFs |
| WBF | O(1%) | exclusive, VBF cuts | Higgs couplings |
| W+j | O(1%) | fully exclusive, decays | PDFs |
| Z+j | O(1-3%) | decays, off-shell effects | PDFs |
| ZH | O(3-5 %) | decays to bb at NLO | Higgs couplings (H-> bb) |
| ZZ | O(4%) | fully exclusive | Trilinear gauge couplings, BSM |
| WW | O(3%) | fully exclusive | Trilinear gauge couplings, BSM |
| top decay | O(1-2 %) | exclusive | Top couplings |
| H -> bb | O(1-2 %) | exclusive, massless | Higgs couplings, boosted |

From K. Melnikov

# Inclusive Jet Production @ NNLO QCD

- Inclusive jet production is a fundamental process for hadron collider phenomenology
- It constrains directly the gluon PDFs, and in that way it has an impact on all theory predictions
- Although NNLO QCD PDFs appear in the market, employing data sets for inclusive jet production, approximations have been made as a full NNLO QCD calculation wasn't available
- Very recently Currie, Glover and Pires (arXiv:1611.01460) have presented the first NNLO QCD results including all subprocesses
- This is the conclusion of a formidable task that started around 1999

# Inclusive Jet Production @ NNLO QCD

- Inclusive jet production is a fundamental process for hadron collider phenomenology
- It constrains directly the gluon PDFs, and in that way it has an impact on all theory predictions
- Although NNLO QCD PDFs appear in the market, employing data sets for inclusive jet production, approximations have been made as a full NNLO QCD calculation wasn't available
- Very recently Currie, Glover and Pires (arXiv:1611.01460) have presented the first NNLO QCD results including all subprocesses
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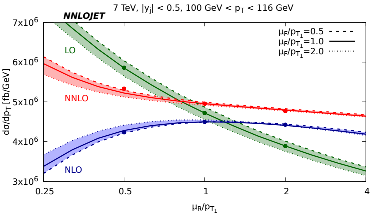
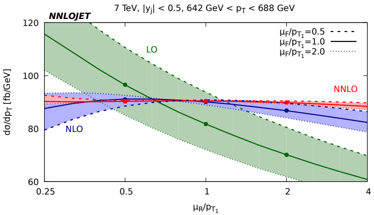
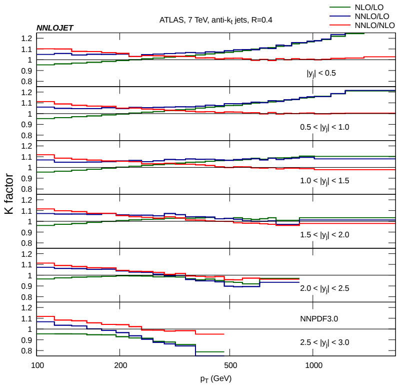


# Structure of Corrections over PS




- Perturbative series converges well for large jet $p_{\mathrm{T}}$
- But $\sim$ 10% NNLO corrections around 100 GeV

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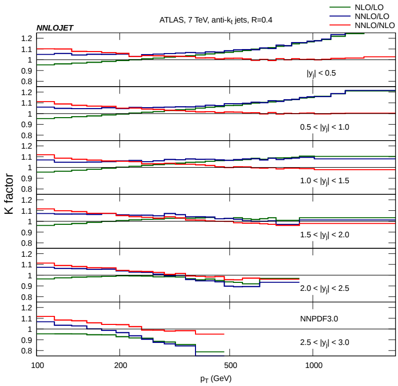


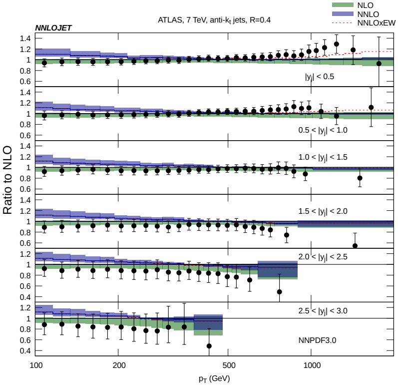


- Perturbative series converges well for large jet $p_\mathrm{T}$
- But $\sim$ 10% NNLO corrections around 100 GeV

- Comparison to ATLAS 7 TeV data shows systematic deviations for low $p_\mathrm{T}$
- We might see an impact on PDFs fits

# Building NNLO QCD Corrections

- Two-loop amplitudes for process $X$
- One-loop amplitudes for process $X + g$
- Tree-level amplitudes for the processes $X + gg$, $X + q\bar{q}$, etc
- Strategy to handle and cancel IR divergences

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- Computing two-loop amplitudes is a significant challenge
- Need fine control of numerical integration of one-loop and tree-level amplitudes over unresolved regions of PS
- Procedures for extracting IR divergences (subtraction/slicing) can be cumbersome. A lot of recent progress: *antenna subtraction*, $q_{\mathrm{T}}$ *subtraction*, $N$*-jettiness slicing*, *sector-improved residue subtraction*, among other

## High Multiplicity Amplitude Calculations

# Numerical Unitarity for Computing Amplitudes

AIM: Write amplitude ($\mathcal{A}$) as a sum of master integrals.

$$\mathcal{A} = \int A = \int \sum_i \frac{N_i}{\rho^1 \dots \rho^{n_i}} = \sum_i c_i \int \frac{t_i^{\mathrm{master}}}{\rho^1 \dots \rho^{n_i}}$$

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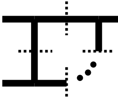
General algorithm:



$\overset{\text{Unitarity}}{\longleftrightarrow}$ [Bern, Dixon, Kosower] $\quad \underset{\{\rho^1,\cdots,\rho^{n_i}\}=0}{\text{Residue}}(A) \quad \overset{\text{Subtraction}}{\longleftrightarrow} \quad N_i = \sum_i c_i t_i$

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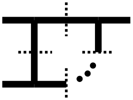

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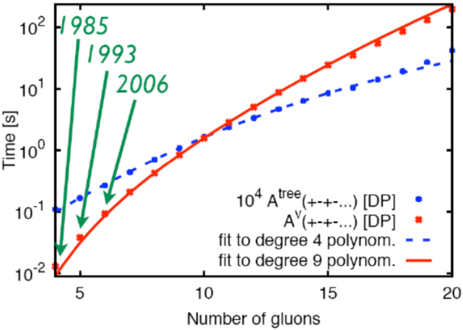
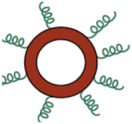
2-loop complications:

- IBPs - how to find basis $\{t_i^{\text{master}}, t_i^{\text{surface}}\}$? [Ita 15]
- Much richer structure of cuts and master integrals
- Handle efficiently the regressions of tensor coefficients

# For 1-loop Amplitudes, A Powerful Technique!



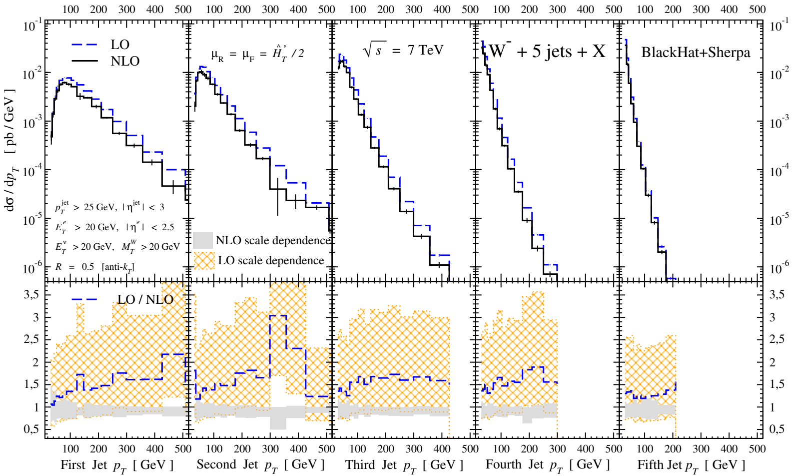
[Giele, Zanderighi arXiv:0806.2152]

**BUT STILL VERY COMPUTER INTENSIVE**

**[ BlackHat + Sherpa ]**

**NTUPLES: STORE AS MUCH INFO AS POSSIBLE DURING YOUR COMPUTATION!**

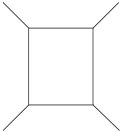
# Jet $p_T$ Spectra at NLO for $W + 5$-Jet Production




- Involves 1-loop amplitudes with 8 particles attached to the loop
- Real radiation with integration over PS of 6(7) particles

- Impressive improvement on the perturbative prediction
- Allows for tests of QCD in highly complex kinematic configurations

# Cuts at One- and Two-Loops in 4-pt Amplitudes



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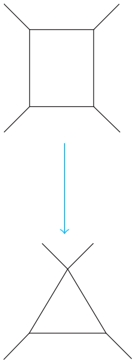

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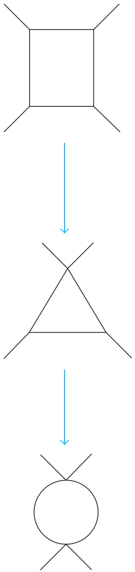

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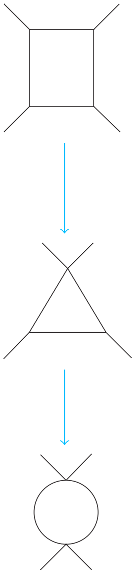

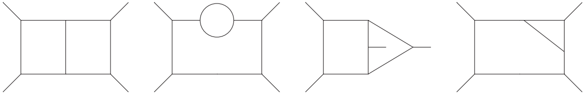

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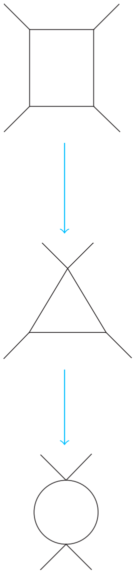

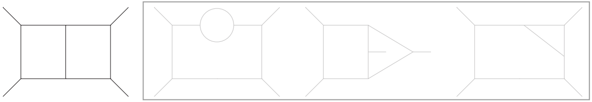

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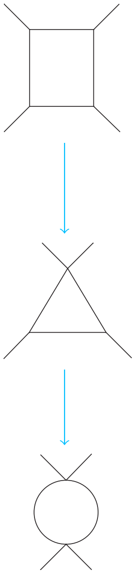

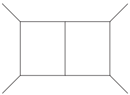

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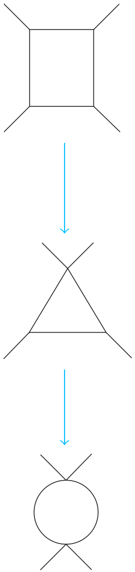

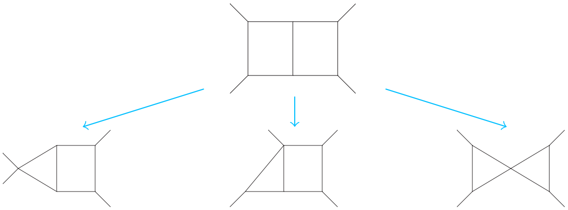

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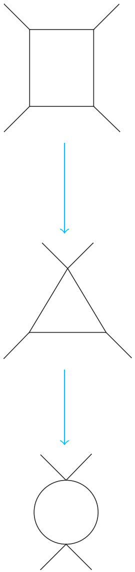

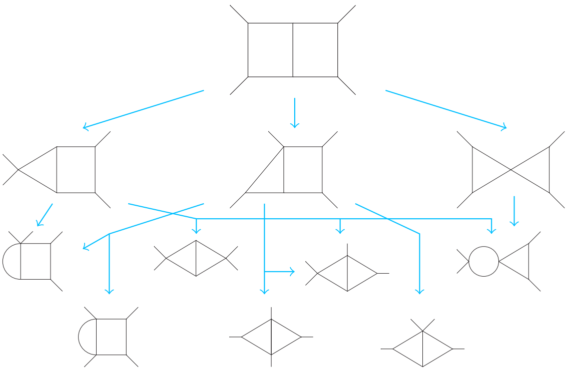

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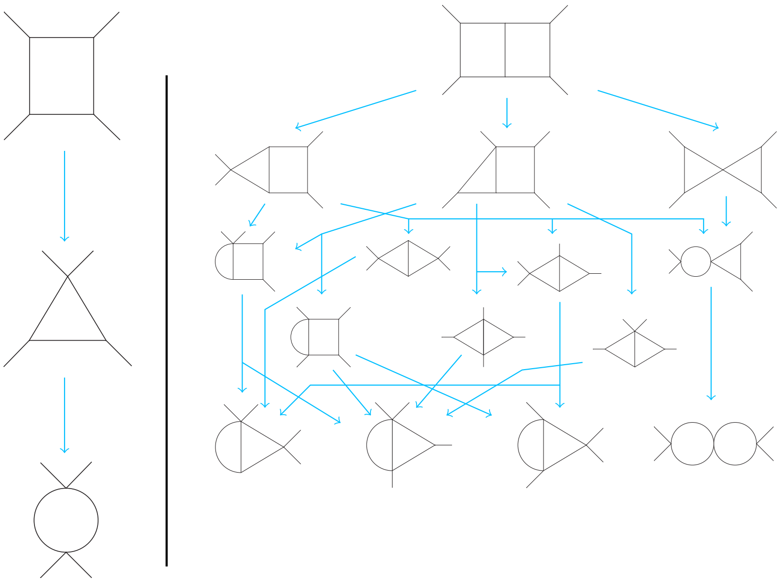

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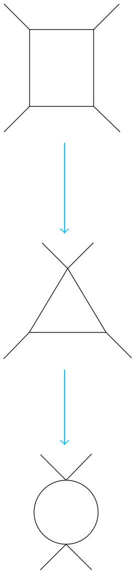

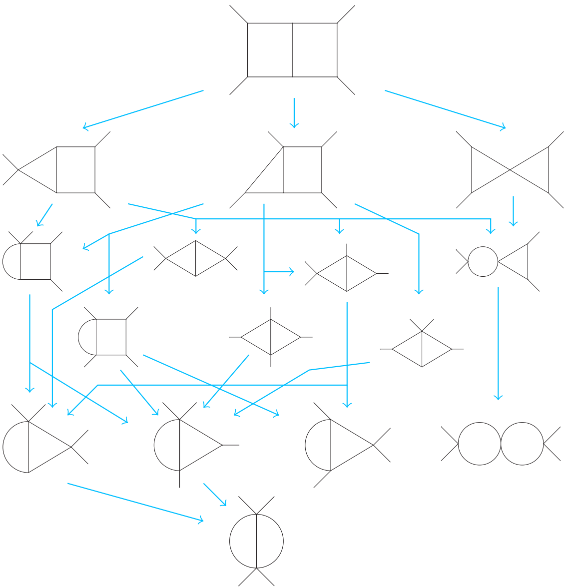

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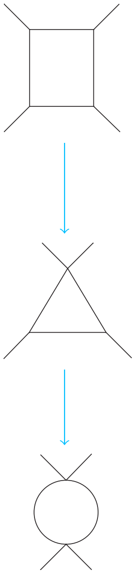
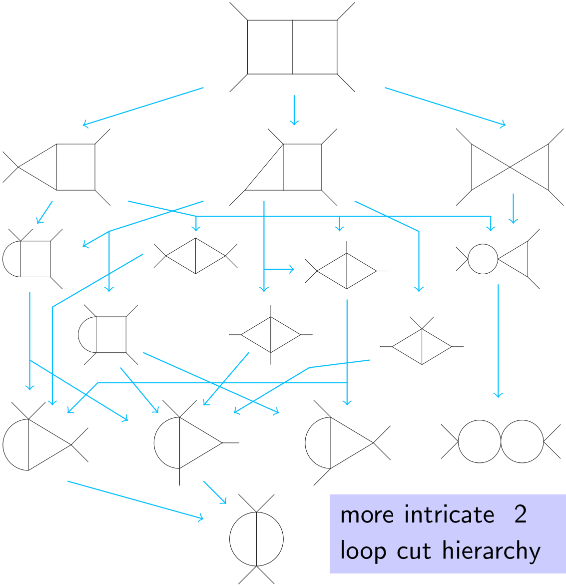




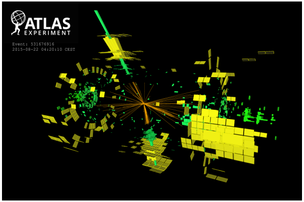
more intricate 2 loop cut hierarchy

# The Path to $5$-pt Two-Loop Amplitudes

- First examples of amplitudes have started to appear
  [Badger, Frellesvig, Mogull, Ochirov, O'Connell, Zhang], [Gehrmann, Henn, Lo Presti], [Dunbar, Jehu, Perkins]
- Important progress on integrand decomposition
  [Ita], [Zhang, Larsen], [Mastrolia, Peraro, Primo, Bobadilla]
- 5-pt (master) integrals also appearing
  [Papadopoulus, Tommasini, Wever], [Gehrmann, Henn, Lo Presti]

# Conclusions

- Particle Physics at High Energies living very active times with new challenges
- Hadron collider phenomenology is entering a precision QCD era to challenge the SM and then find answers to outstanding problems
- This is also a requirement in order to exploit in full the physics potential of current (LHC) and future (ILC, FCC, CEPC) colliders
- Theoretical progress has been steady and with new ideas, new techniques and computer power we should be able to reach unprecedented levels of precision



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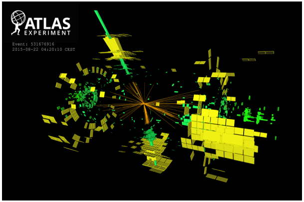


Thanks!