pQCD (and SM) physics at the LHC

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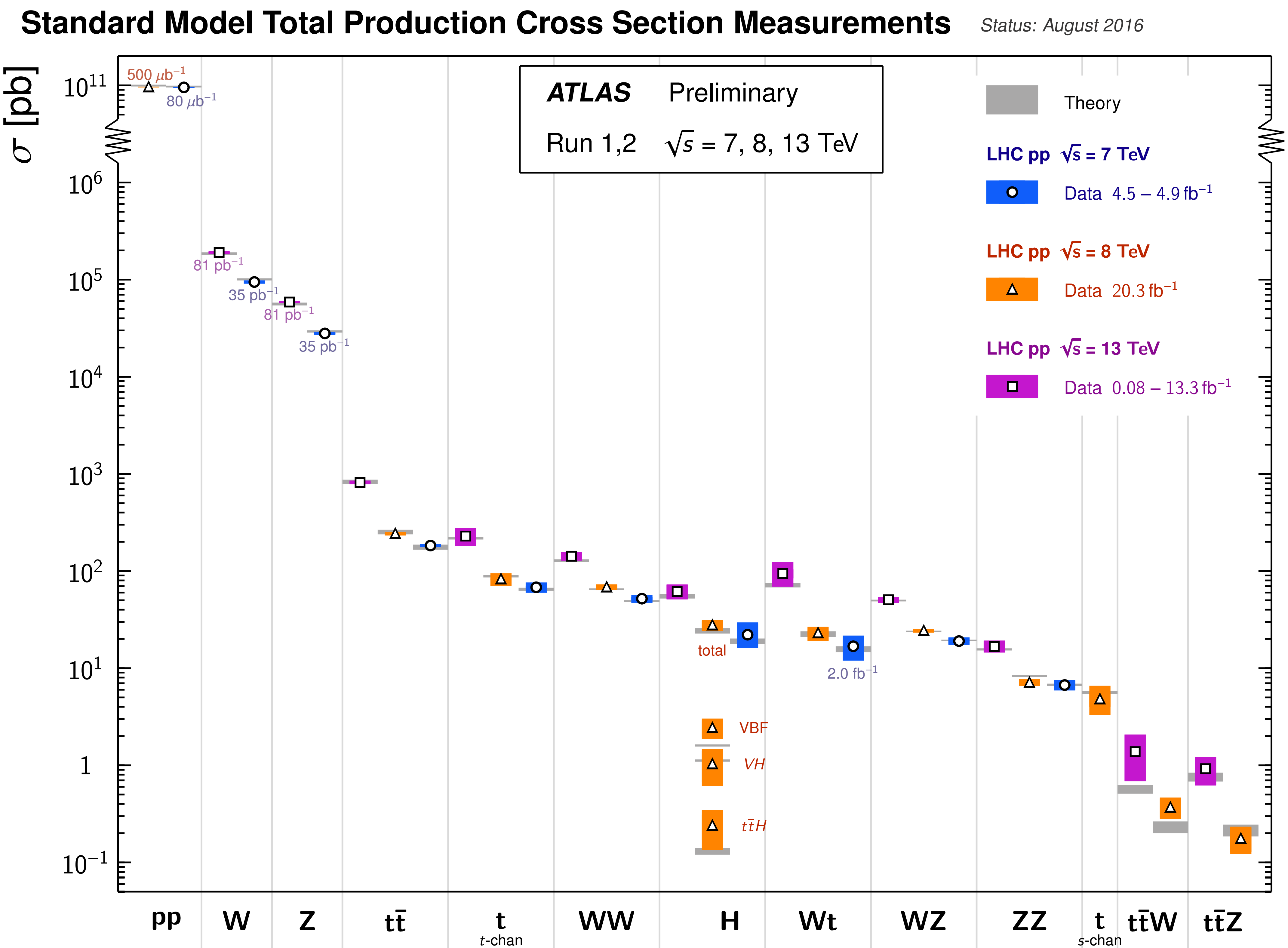
Who, How, When, Where ?

Who, How, When, Where ?

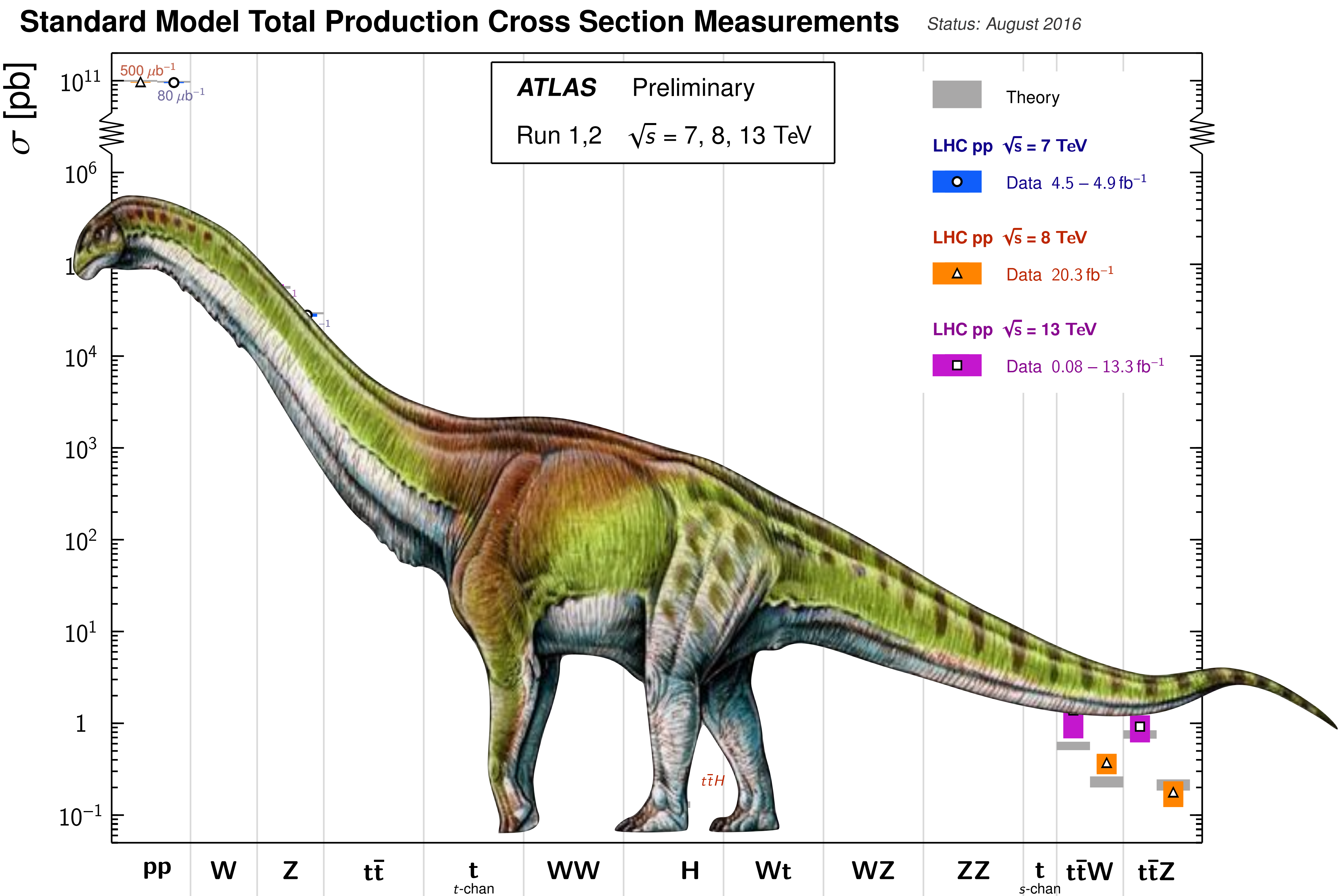

- CONMEBOL -
LIBERTADORES

- LHC incredibly successful at 7 , 8 & 13 TeV (Runs I and II)



- Everything SM like (including Higgs)

- LHC incredibly successful at 7 , 8 & 13 TeV (Runs I and II)



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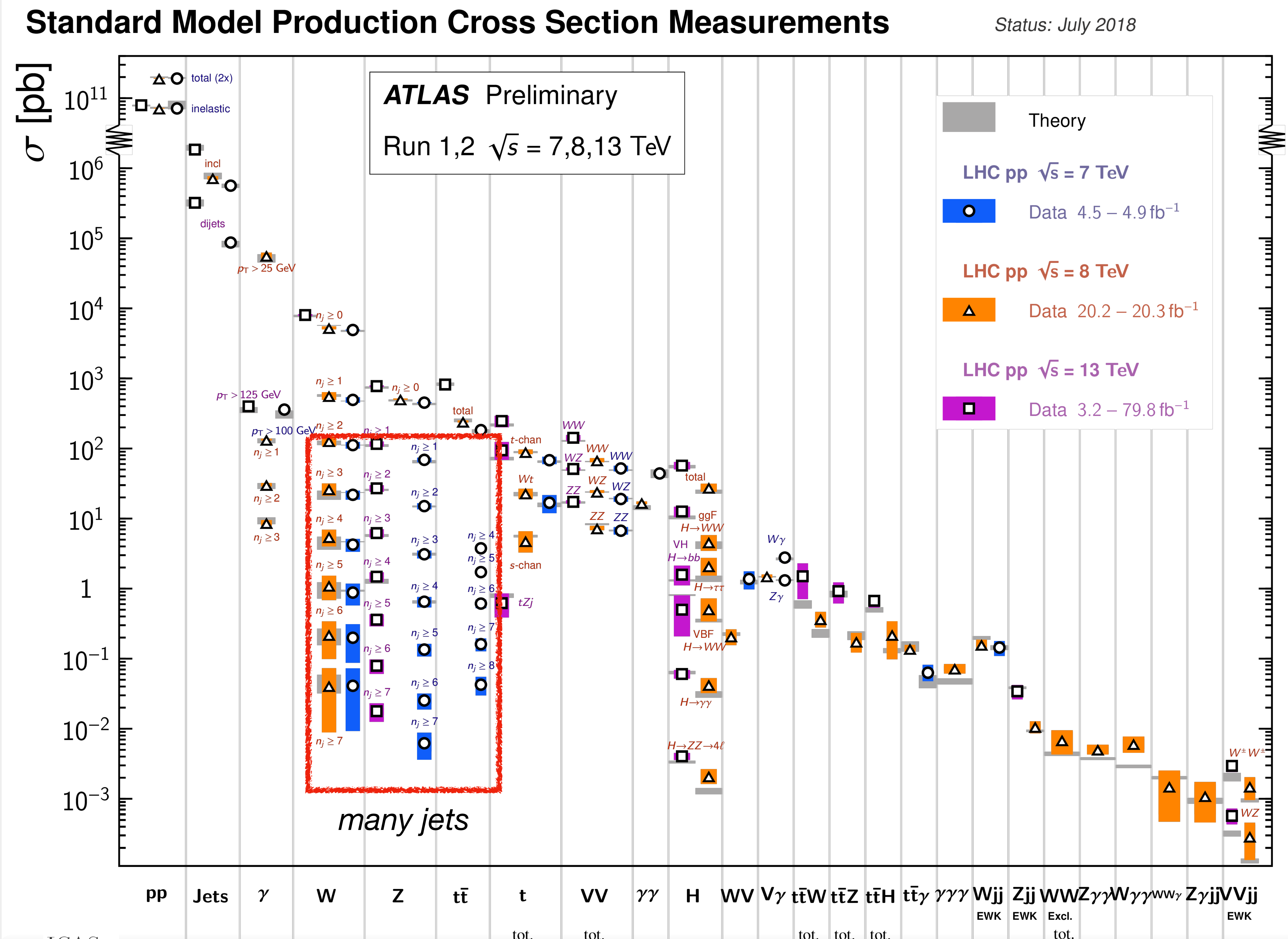
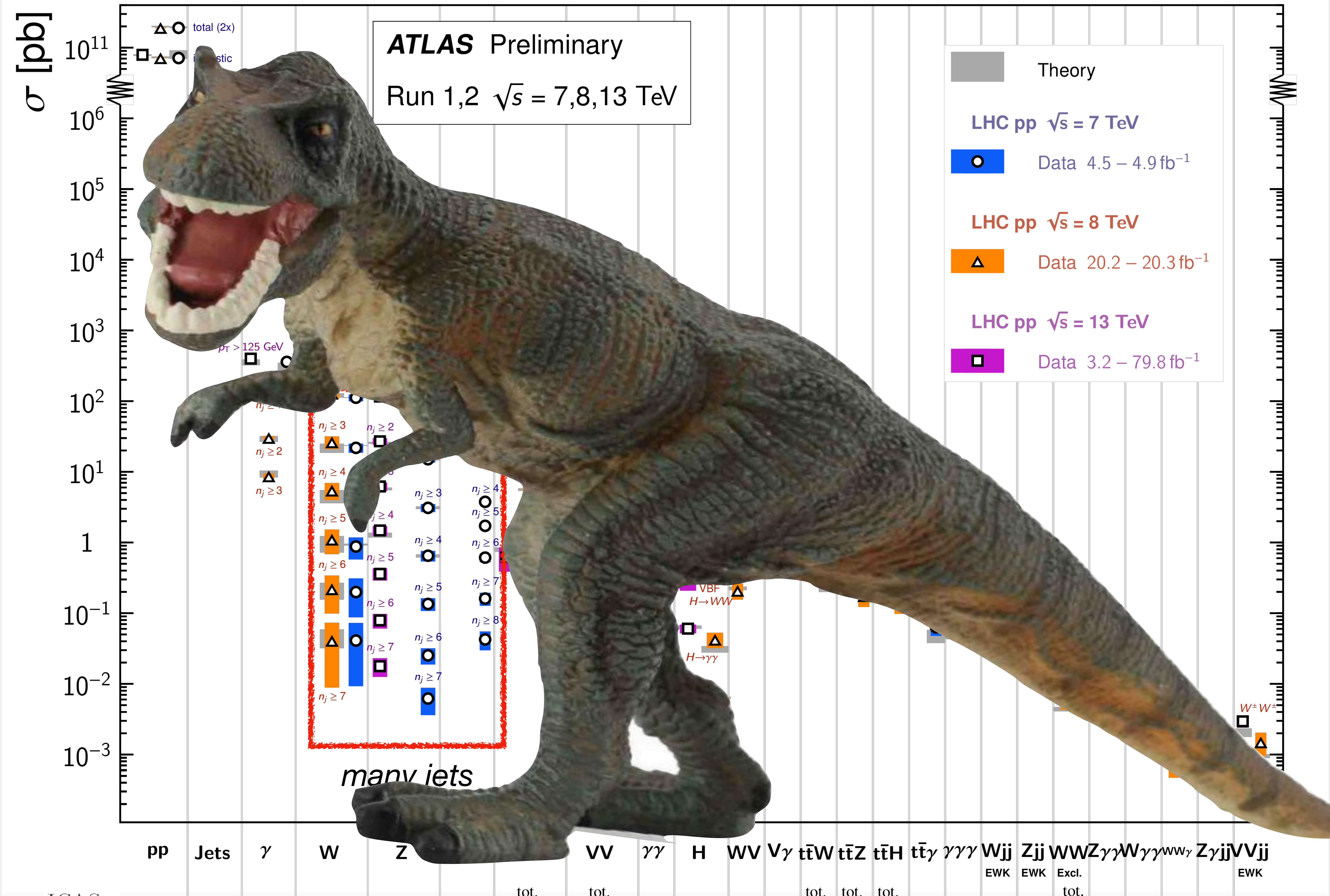

Standard Model Production Cross Section Measurements
Status: July 2018
ATLAS Preliminary
Run 1,2 $\sqrt{s}$ = 7,8,13 TeV
σ [pb]
Theory
LHC pp $\sqrt{s}$ = 7 TeV
Data 4.5 – 4.9 fb^{-1}
LHC pp $\sqrt{s}$ = 8 TeV
Data 20.2 – 20.3 fb^{-1}
LHC pp $\sqrt{s}$ = 13 TeV
Data 3.2 – 79.8 fb^{-1}
total (2x)
inelastic
incl
dijets
p_T > 25 GeV
p_T > 125 GeV
p_T > 100 GeV
total
t-chan
Wt
s-chan
tZj
ggF H→WW
VH H→bb
H→ττ
VBF H→WW
H→γγ
H→ZZ→4ℓ
Wγ
Zγ
W±W±
WZ
many jets
pp
Jets
γ
W
Z
tt̄
t
VV
γγ
H
WV
Vγ
tt̄W
tt̄Z
tt̄H
tt̄γ
γγγ
Wjj EWK
Zjj EWK
WW Excl.
Zγγ
Wγγ
WWγ
Zγjj
VVjj EWK
tot.

Standard Model Production Cross Section Measurements



But.... there should be Physics Beyond the Standard Model (BSM)

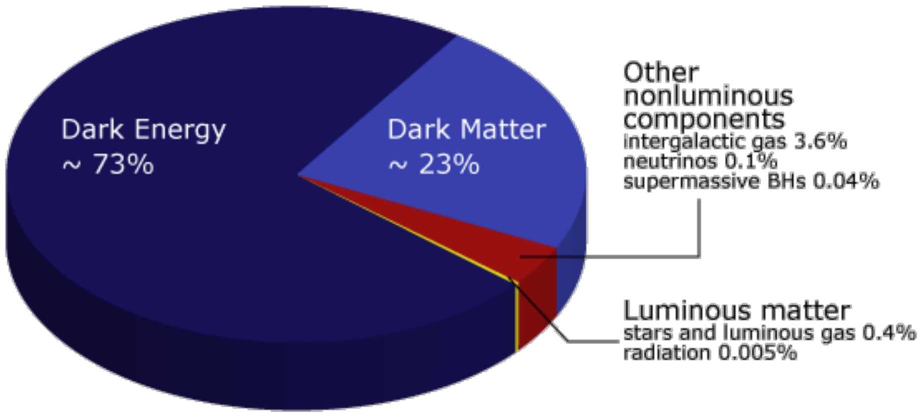
- Lacks description of Quantum Gravity
- Hierarchy, naturalness problems

  Gravity is ~40 orders of magnitude weaker than EM in atom

  13 orders of magnitude between lightest and heaviest particle

  Finer tuning in Higgs sector

- No candidate for Dark Matter !!
  >20% of universe
- Matter-antimatter asymmetry
- ....



There are(?) TH candidates, but search is DRIVEN BY EXPERIMENTS now

Excitement after Higgs Discovery…

Excitement after Higgs Discovery…

..some level of concern/depression in the community

electron	(1897) Thompson
positron	(1932) Anderson
muon	(1937) Cosmic radiation-Cloud chamber
neutrino electron	(1956) Savannah River Plant
neutrino muon	(1962) BNL
u,d,s	(1969) SLAC
charm	(1974) SLAC-BNL
tau	(1975) SLAC-SPEAR-LBL
bottom	(1977) E288
gluon	(1979) DORIS/PETRA
W/Z	(1983) UA1
top	(1995) Tevatron
neutrino tau	(2000) DONUT
Higgs	(2012) LHC

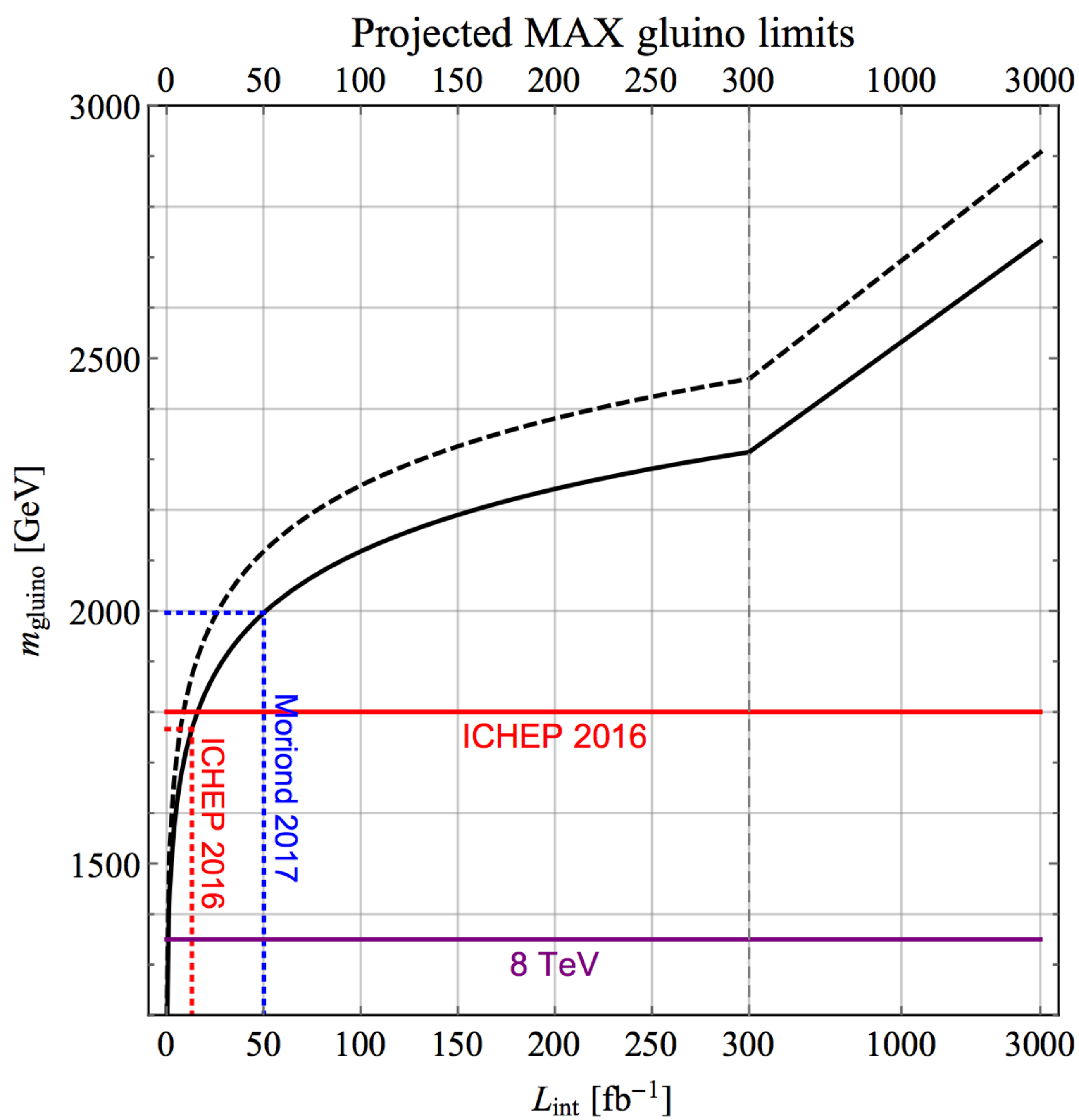
One big discovery by experiment…

- Most direct searches for new physics have been carried out with approx. 35 fb^{-1}, so only 1% of the data of the entire LHC program

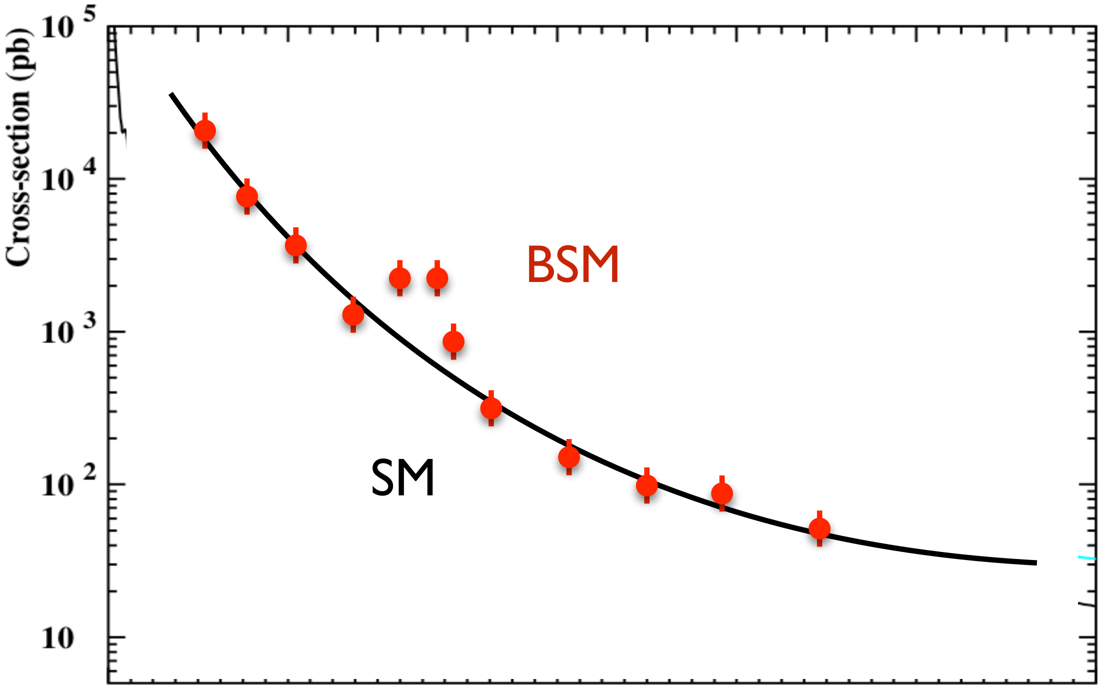
- There is plenty of room for discoveries yet

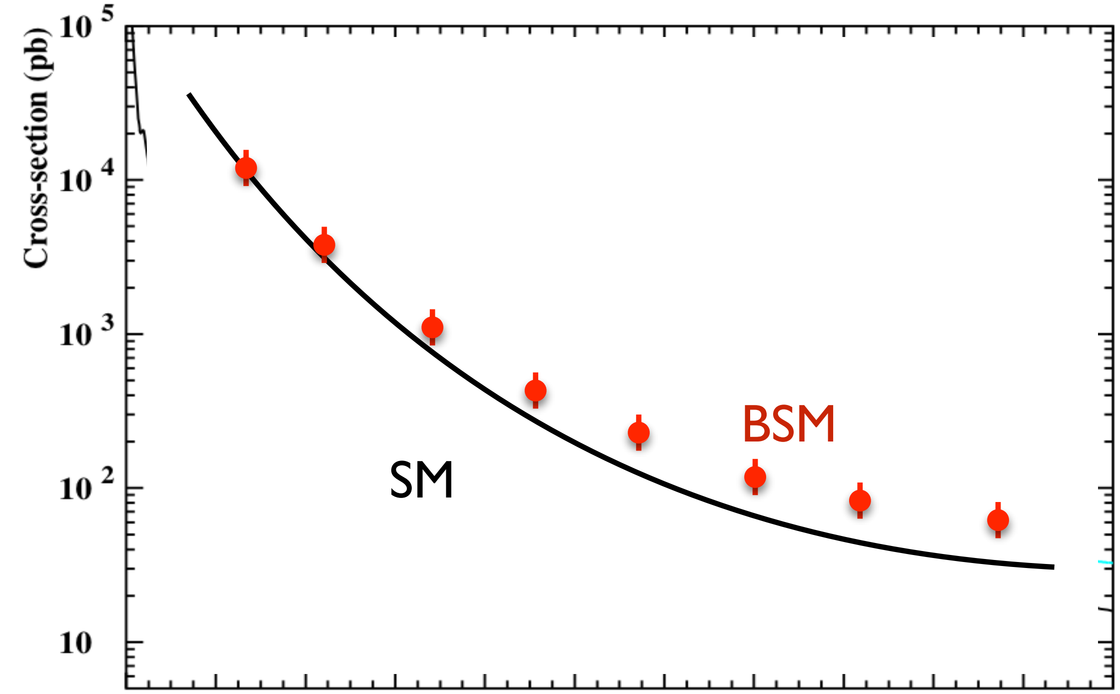
- It will take time (doubling time of the luminosity should be counted in several years)

from M. Kado

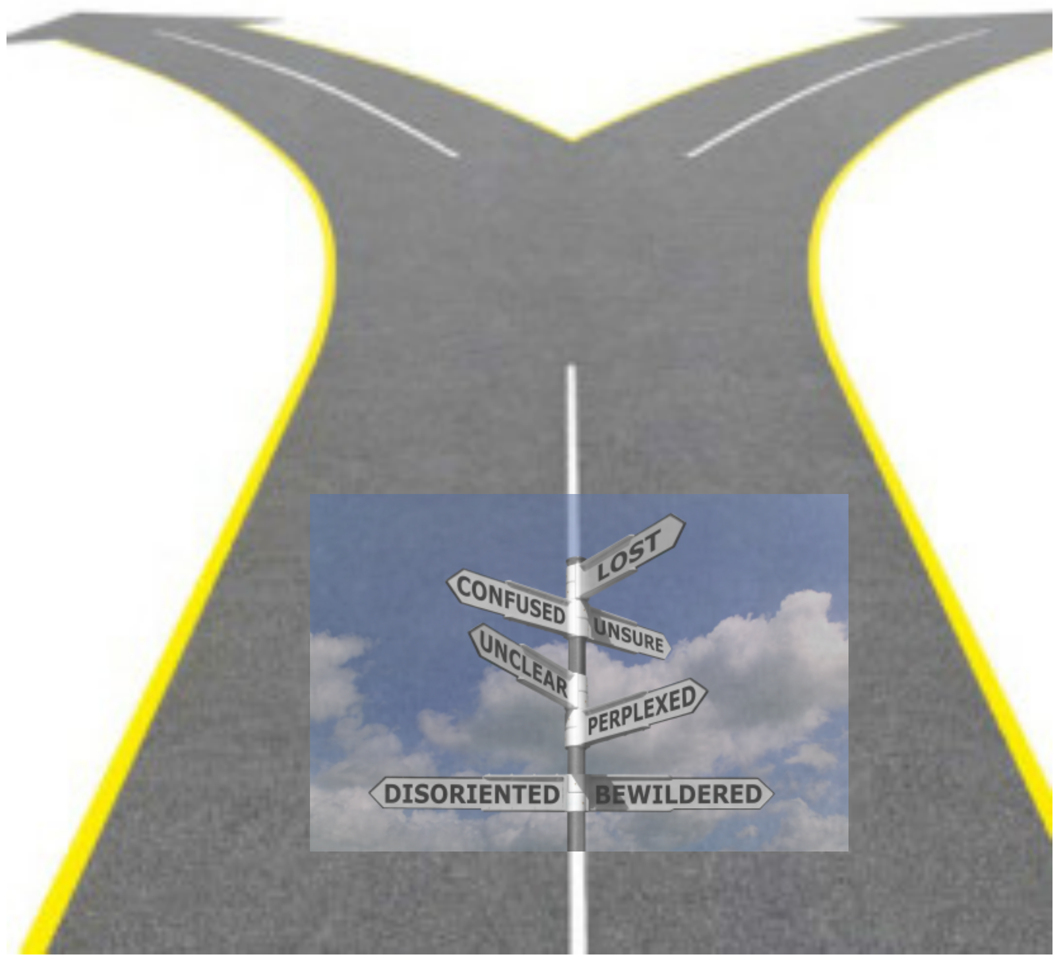


From D. Shih (from G. Salam)

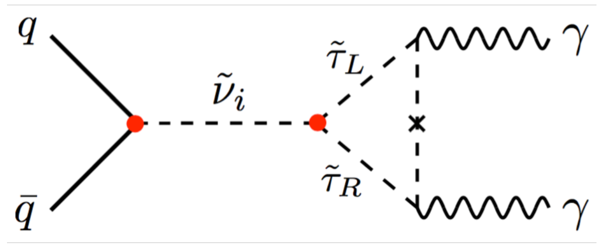


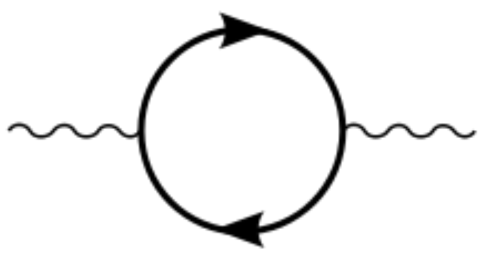


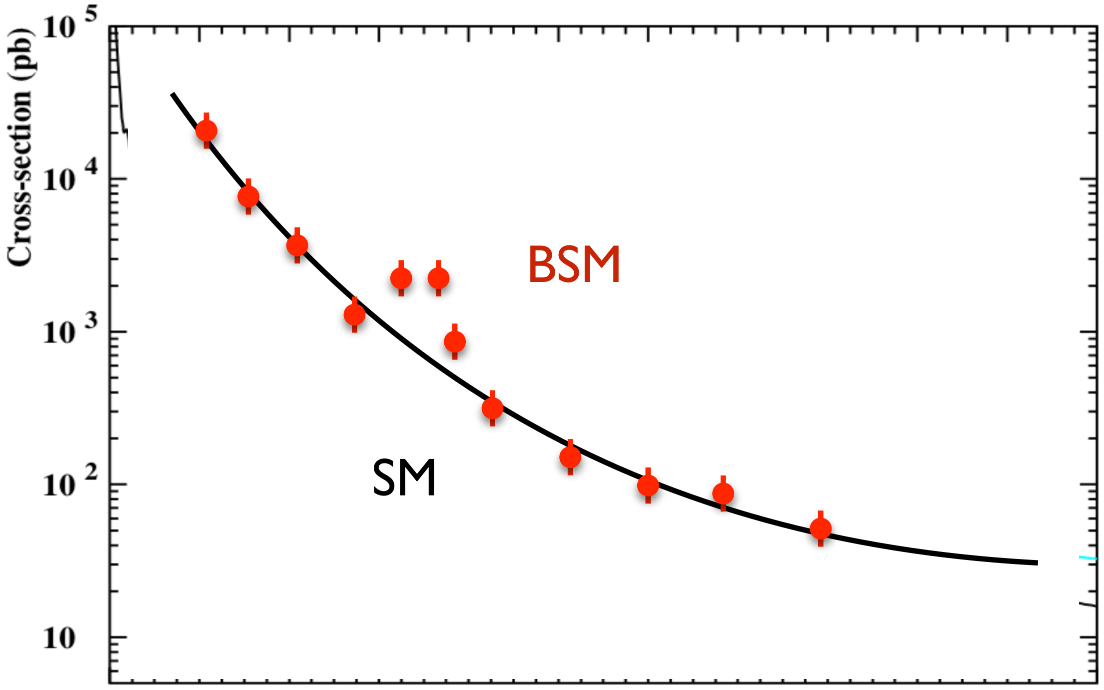
Search for
new *states*
Resonances
"Descriptive TH"

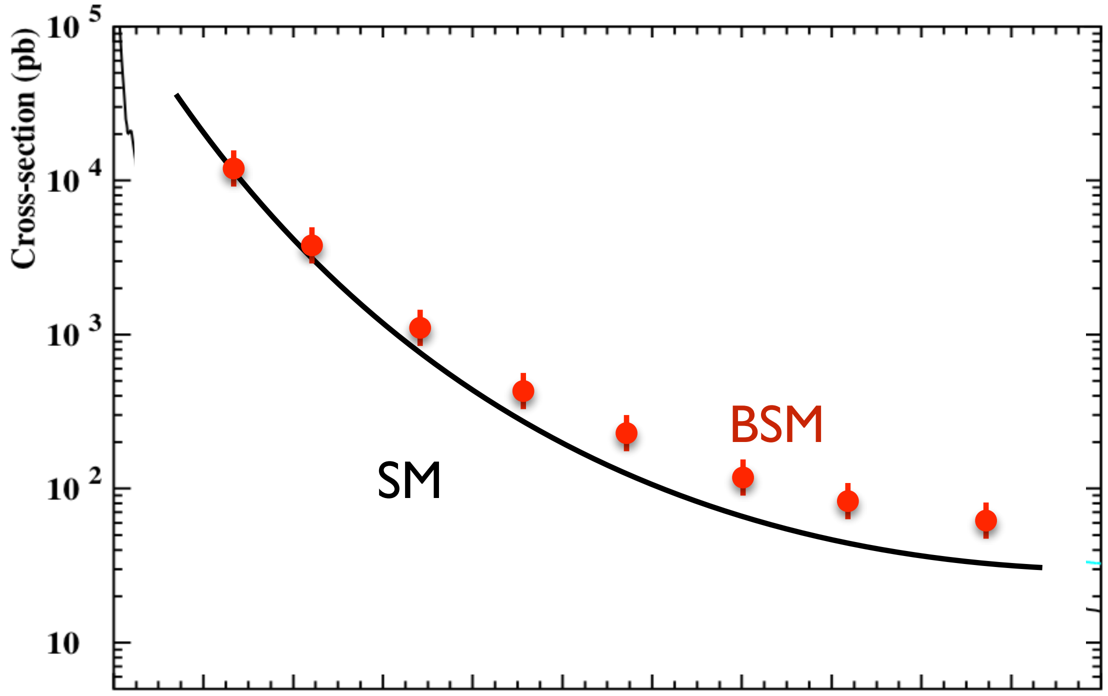


Search for new
interactions
Deviations from TH
"Precision TH"









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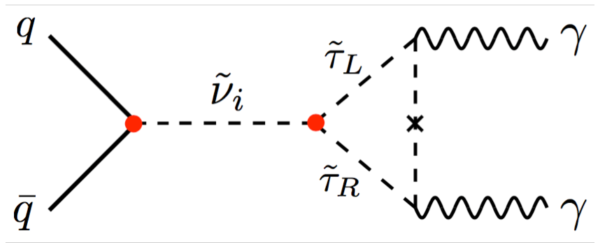

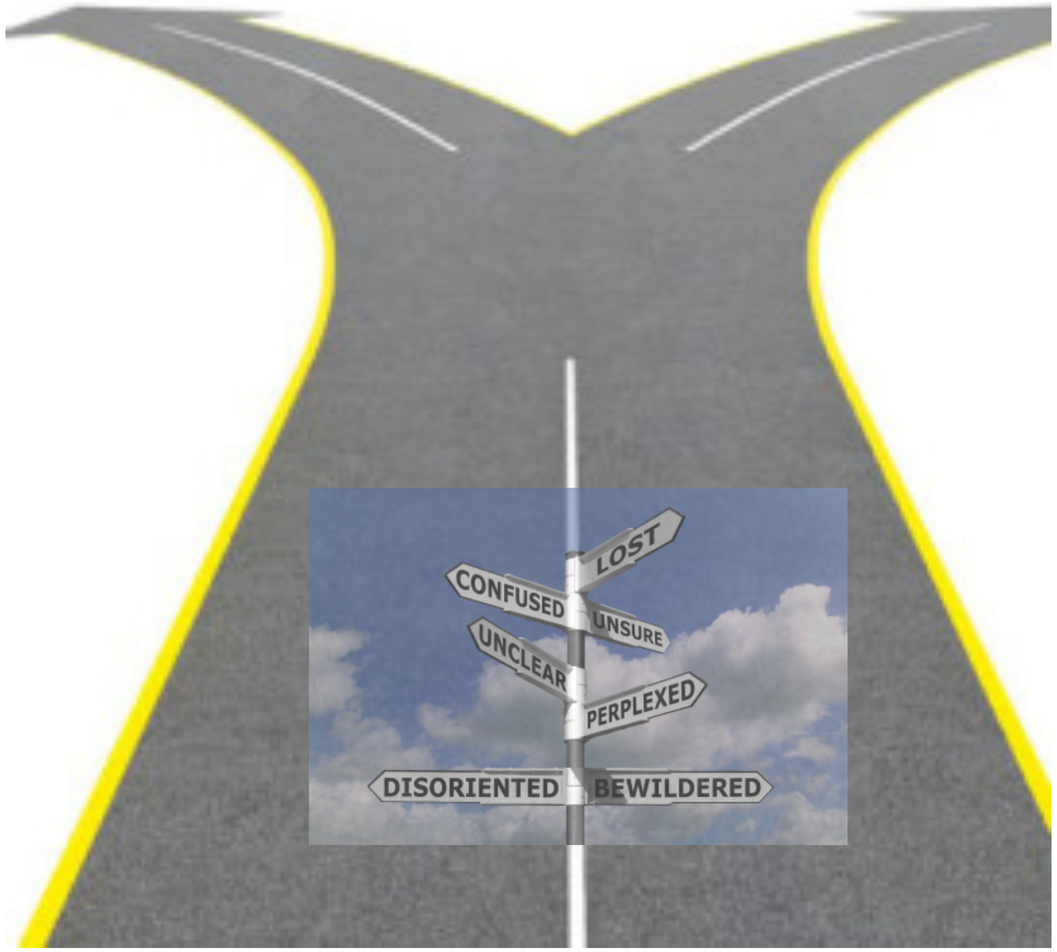

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Deviations from TH
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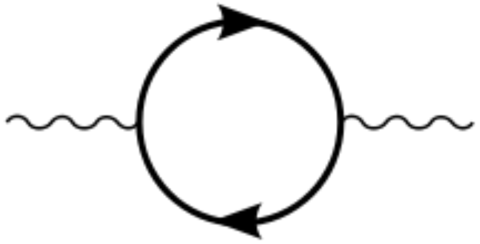


- Need for precision ~ 1% EXP-TH accuracy

- Non-resonant BSM : no new particle observed (too heavy)
- Corrections due to the exchange of new heavy states can be parametrized by low-energy effective Lagrangian EFT

$$\mathcal{L}_{\rm SM} = \mathcal{L}_{\rm SM}^{(4)} + \frac{1}{\Lambda}\sum_k C_k^{(5)} Q_k^{(5)} + \frac{1}{\Lambda^2}\sum_k C_k^{(6)} Q_k^{(6)} + \mathcal{O}\left(\frac{1}{\Lambda^3}\right)$$

scale of new physics

Add operators of dimension 6 : gauge invariant, respect basic conservation laws (CP, L and B numbers), Custodial symmetry, etc

59 operators without flavor structure

consistent approach: better than using anomalous couplings

X^3		φ^6 and $\varphi^4 D^2$		$\psi^2\varphi^3$	
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	Q_φ	$(\varphi^\dagger\varphi)^3$	$Q_{e\varphi}$	$(\varphi^\dagger\varphi)(\bar l_p e_r \varphi)$
$Q_{\widetilde G}$	$f^{ABC} \widetilde G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	$Q_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$	$Q_{u\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p u_r \widetilde\varphi)$
Q_W	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$\left(\varphi^\dagger D^\mu\varphi\right)^\star \left(\varphi^\dagger D_\mu\varphi\right)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p d_r \varphi)$
$Q_{\widetilde W}$	$\varepsilon^{IJK} \widetilde W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$				
$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G^A_{\mu\nu} G^{A\mu\nu}$	Q_{eW}	$(\bar l_p \sigma^{\mu\nu} e_r)\tau^I \varphi W^I_{\mu\nu}$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar l_p \gamma^\mu l_r)$
$Q_{\varphi\widetilde G}$	$\varphi^\dagger\varphi\, \widetilde G^A_{\mu\nu} G^{A\mu\nu}$	Q_{eB}	$(\bar l_p \sigma^{\mu\nu} e_r)\varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu \varphi)(\bar l_p \tau^I \gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W^I_{\mu\nu} W^{I\mu\nu}$	Q_{uG}	$(\bar q_p \sigma^{\mu\nu} T^A u_r)\widetilde\varphi\, G^A_{\mu\nu}$	$Q_{\varphi e}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar e_p \gamma^\mu e_r)$
$Q_{\varphi\widetilde W}$	$\varphi^\dagger\varphi\, \widetilde W^I_{\mu\nu} W^{I\mu\nu}$	Q_{uW}	$(\bar q_p \sigma^{\mu\nu} u_r)\tau^I \widetilde\varphi\, W^I_{\mu\nu}$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar q_p \gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu} B^{\mu\nu}$	Q_{uB}	$(\bar q_p \sigma^{\mu\nu} u_r)\widetilde\varphi\, B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu \varphi)(\bar q_p \tau^I \gamma^\mu q_r)$
$Q_{\varphi\widetilde B}$	$\varphi^\dagger\varphi\, \widetilde B_{\mu\nu} B^{\mu\nu}$	Q_{dG}	$(\bar q_p \sigma^{\mu\nu} T^A d_r)\varphi\, G^A_{\mu\nu}$	$Q_{\varphi u}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar u_p \gamma^\mu u_r)$
$Q_{\varphi WB}$	$\varphi^\dagger\tau^I\varphi\, W^I_{\mu\nu} B^{\mu\nu}$	Q_{dW}	$(\bar q_p \sigma^{\mu\nu} d_r)\tau^I \varphi\, W^I_{\mu\nu}$	$Q_{\varphi d}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar d_p \gamma^\mu d_r)$
$Q_{\varphi\widetilde WB}$	$\varphi^\dagger\tau^I\varphi\, \widetilde W^I_{\mu\nu} B^{\mu\nu}$	Q_{dB}	$(\bar q_p \sigma^{\mu\nu} d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde\varphi^\dagger D_\mu\varphi)(\bar u_p \gamma^\mu d_r)$

- EXP and TH : Precision is the name of the game

Outline

pQCD @ LHC

precision perturbative production

- EXP and TH : Precision is the name of the game

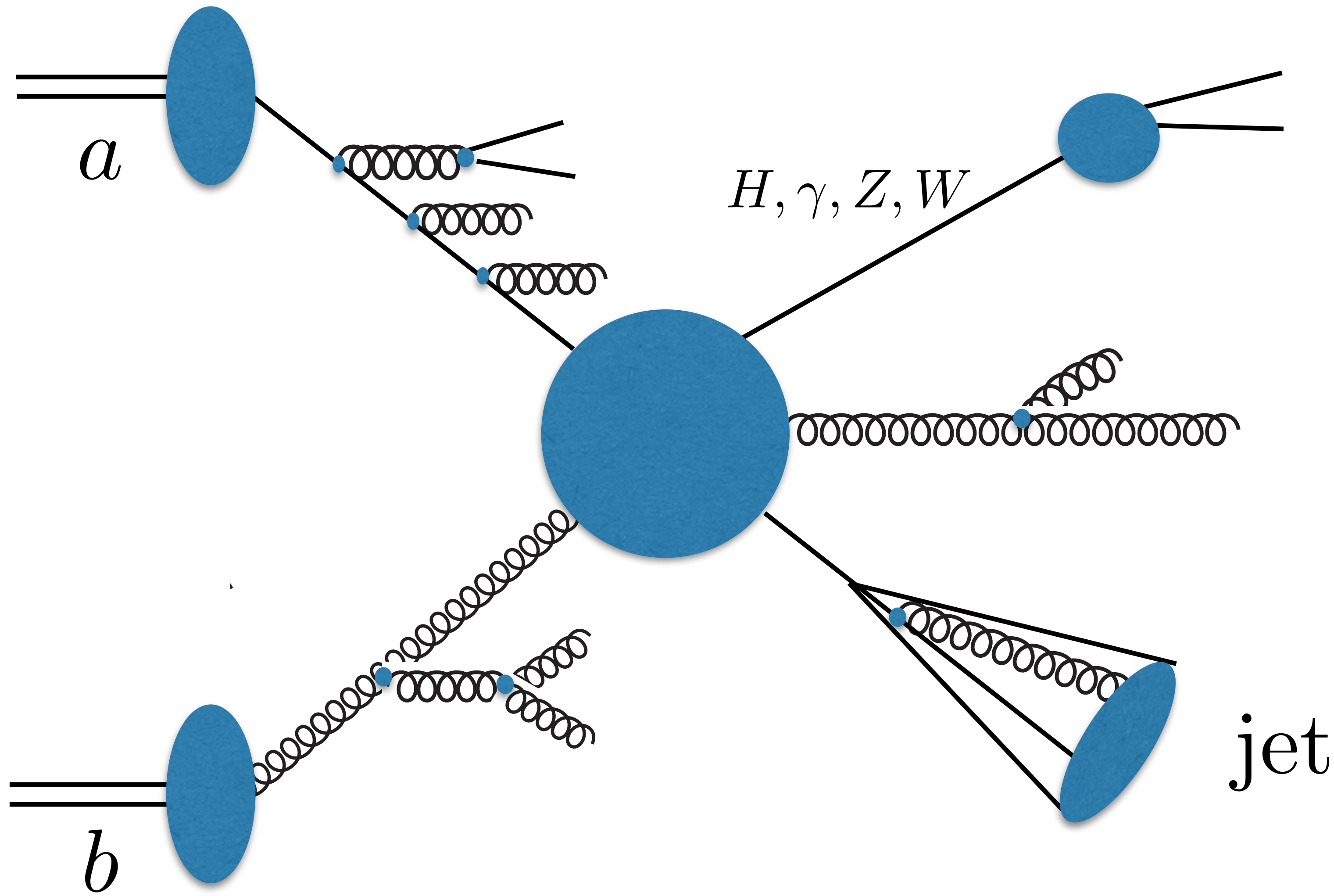
Outline

pQCD @ LHC

precision perturbative production

- PDFs
- NLO
- NNLO and even N^3LO
- EW/QED corrections
- example: 2H production
- Conclusions

- In the LHC era, QCD is everywhere!



non-perturbative parton distributions

$$d\sigma = \sum_{ab} \int dx_a \int dx_b \, f_a(x_a, \mu_F^2) f_b(x_b, \mu_F^2) \times d\hat{\sigma}_{ab}(x_a, x_b, Q^2, \alpha_s(\mu_R^2)) + \mathcal{O}\left(\left(\frac{\Lambda}{Q}\right)^m\right)$$

perturbative partonic cross-section

- Require precision for perturbative and non-perturbative contribution

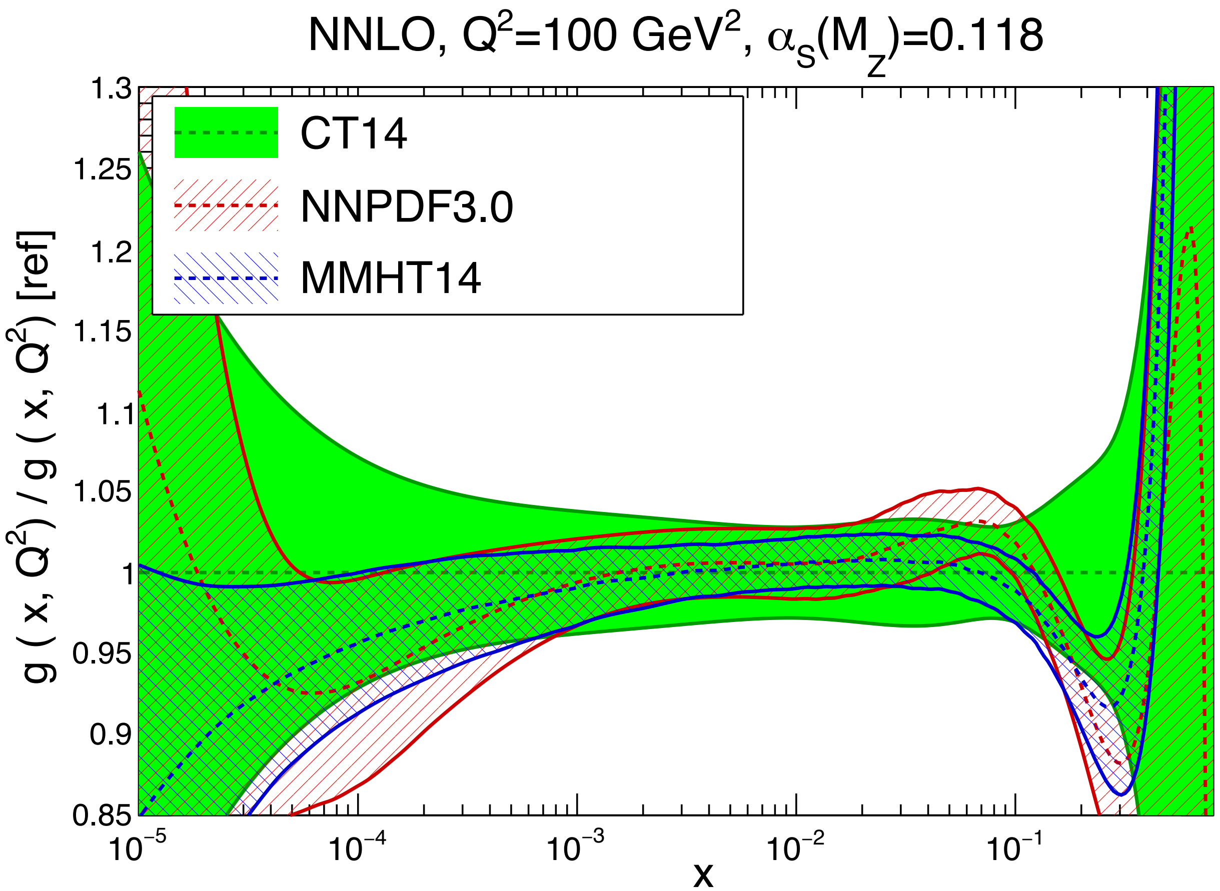
PDFs

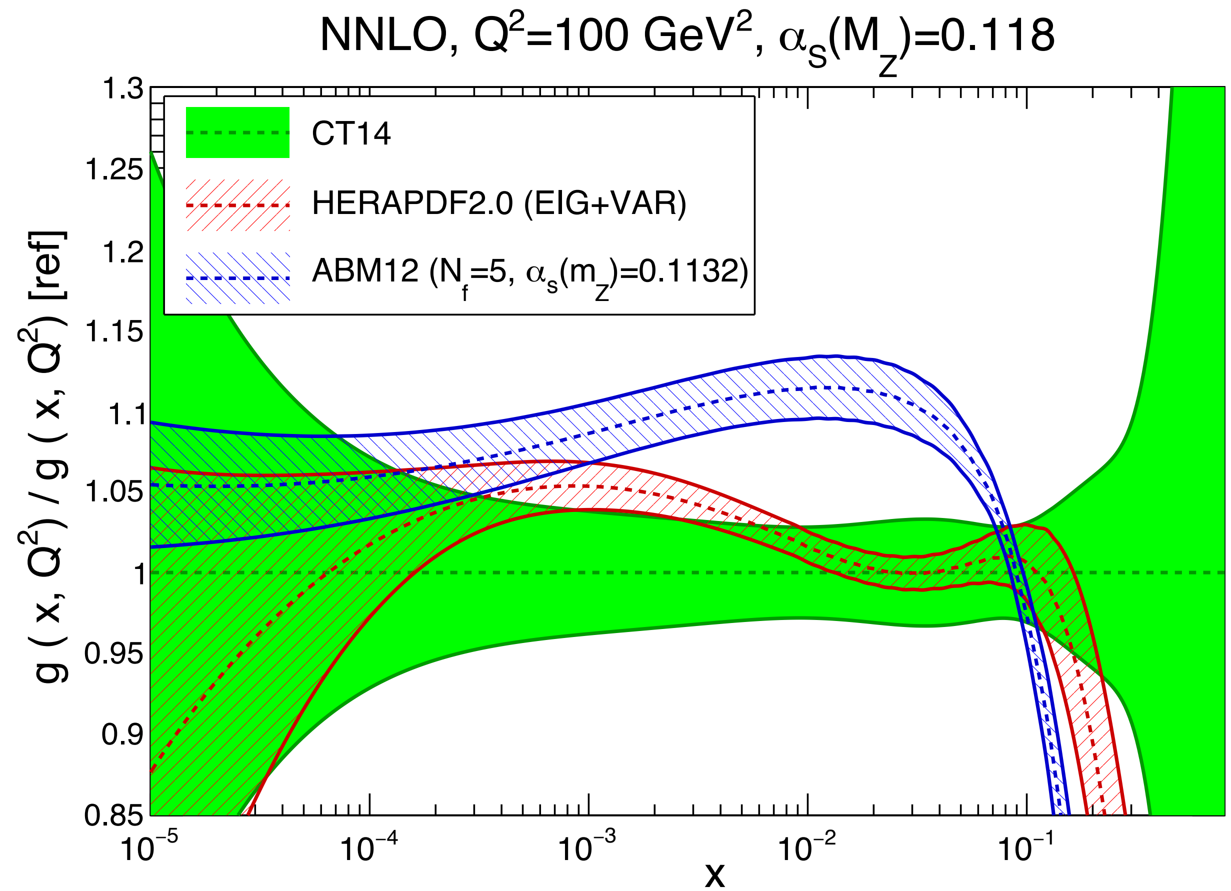
- Several groups provide pdf fits + uncertainties
- Differ by: data input, TH/bias, HQ treatment, coupling, etc

set	H.O.	data	$\alpha_s(M_Z)@NNLO$	uncertainty	HQ
MMHT14	NNLO	DIS+DY+Jets+LHC	0,118	Hessian (dynamical tolerance)	GM-VFN (ACOT+TR')
CT14	NNLO	DIS+DY+Jets+LHC	0,118	Hessian (dynamical tolerance)	GM-VFN (SACOT-X)
NNPDF 3	NNLO	DIS+DY+Jets+LHC	0,118	Monte Carlo	GM-VFN (FONLL)
ABM	NNLO	DIS+DY(f.t.)+DY-tT(LHC)	0,1132	Hessian	FFN BMSN
(G)JR	NNLO	DIS+DY(f.t.)+ some jet	0,1124	Hessian	FFN (VFN massless)
HERA PDF	NNLO	only DIS HERA	0,1176	Hessian	GM-VFN (ACOT+TR')

PDF4LHC

Most "global" sets show reasonable agreement (others not so much)





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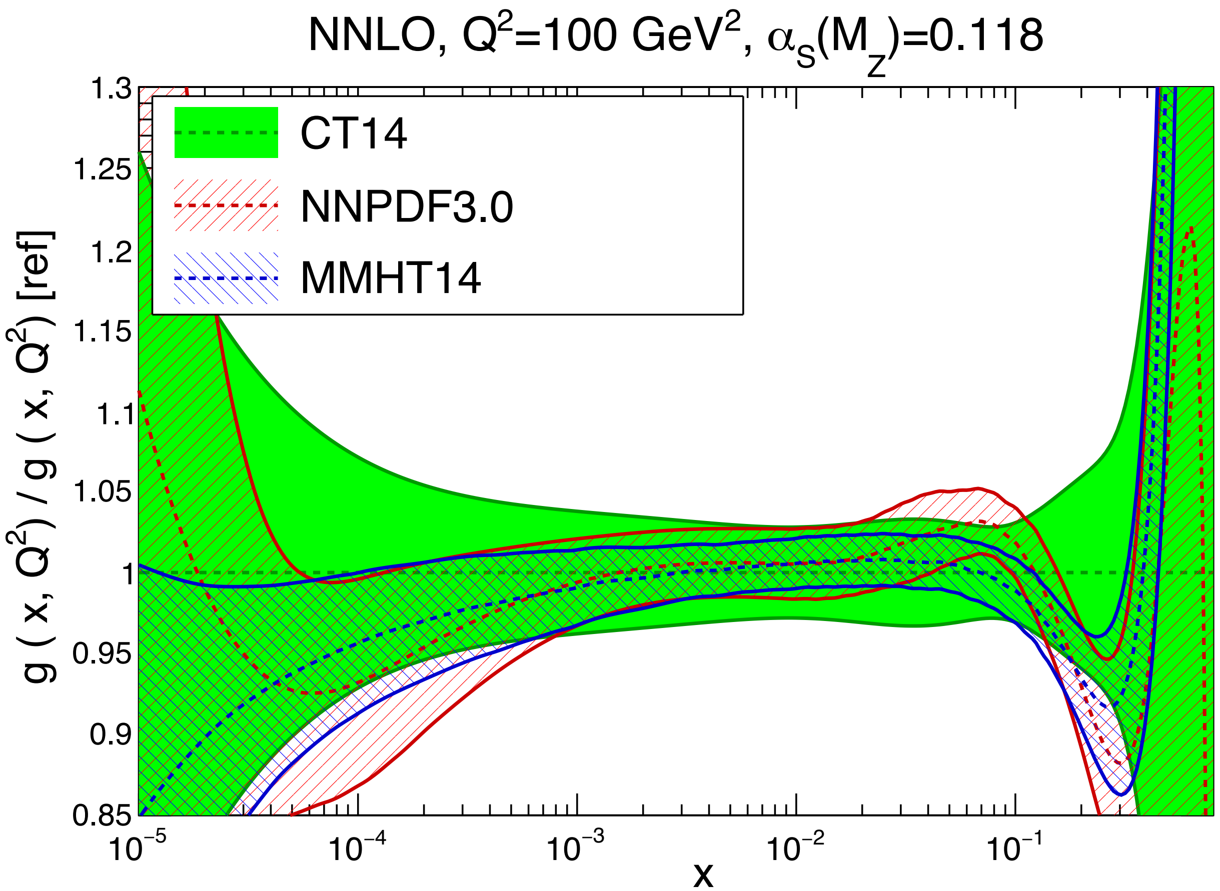
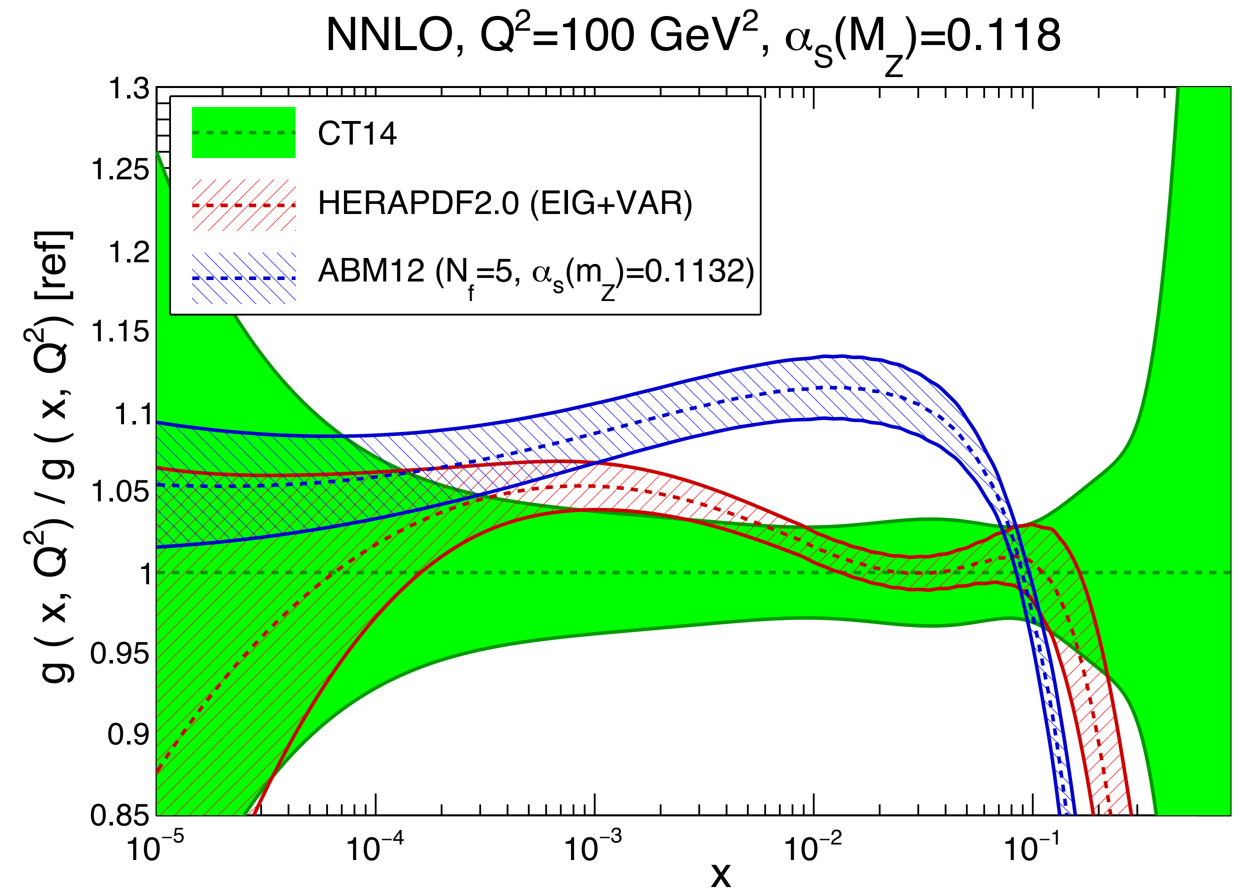




PDF4LHC: combination of 3 global in a single combined PDF set

optimized sets of Hessian eigenvectors or Monte Carlo replicas

$$\alpha_s(m_Z^2) = 0.1180 \pm 0.0015$$

Reduced uncertainty from previous prescription (envelope) up to factor of 2

PV: looks a bit too optimistic…

arXiv.org > hep-ph > arXiv:1510.03865

High Energy Physics – Phenomenology

PDF4LHC recommendations for LHC Run II

Jon Butterworth, Stefano Carrazza, Amanda Cooper-Sarkar, Albert De Roeck, Joel Feltesse, Stefano Forte, Jun Gao, Sasha Glazov, Joey Huston, Zahari Kassabov, Ronan McNulty, Andreas Morsch, Pavel Nadolsky, Voica Radescu, Juan Rojo, Robert Thorne

(Submitted on 13 Oct 2015 (v1), last revised 12 Nov 2015 (this version, v2))

We provide an updated recommendation for the usage of sets of parton distribution functions (PDFs) and the assessment of PDF and PDF+α_s uncertainties suitable for applications at the LHC Run II. We review developments since the previous PDF4LHC recommendation, and discuss and compare the new generation of PDFs, which include substantial information from experimental data from the Run I of the LHC. We then propose a new prescription for the combination of a suitable subset of the available PDF sets, which is presented in terms of a single combined PDF set. We finally discuss tools which allow for the delivery of this combined set in terms of optimized sets of Hessian eigenvectors or Monte Carlo replicas, and their usage, and provide some examples of their application to LHC phenomenology.

arXiv.org > hep-ph > arXiv:1603.08906

High Energy Physics – Phenomenology

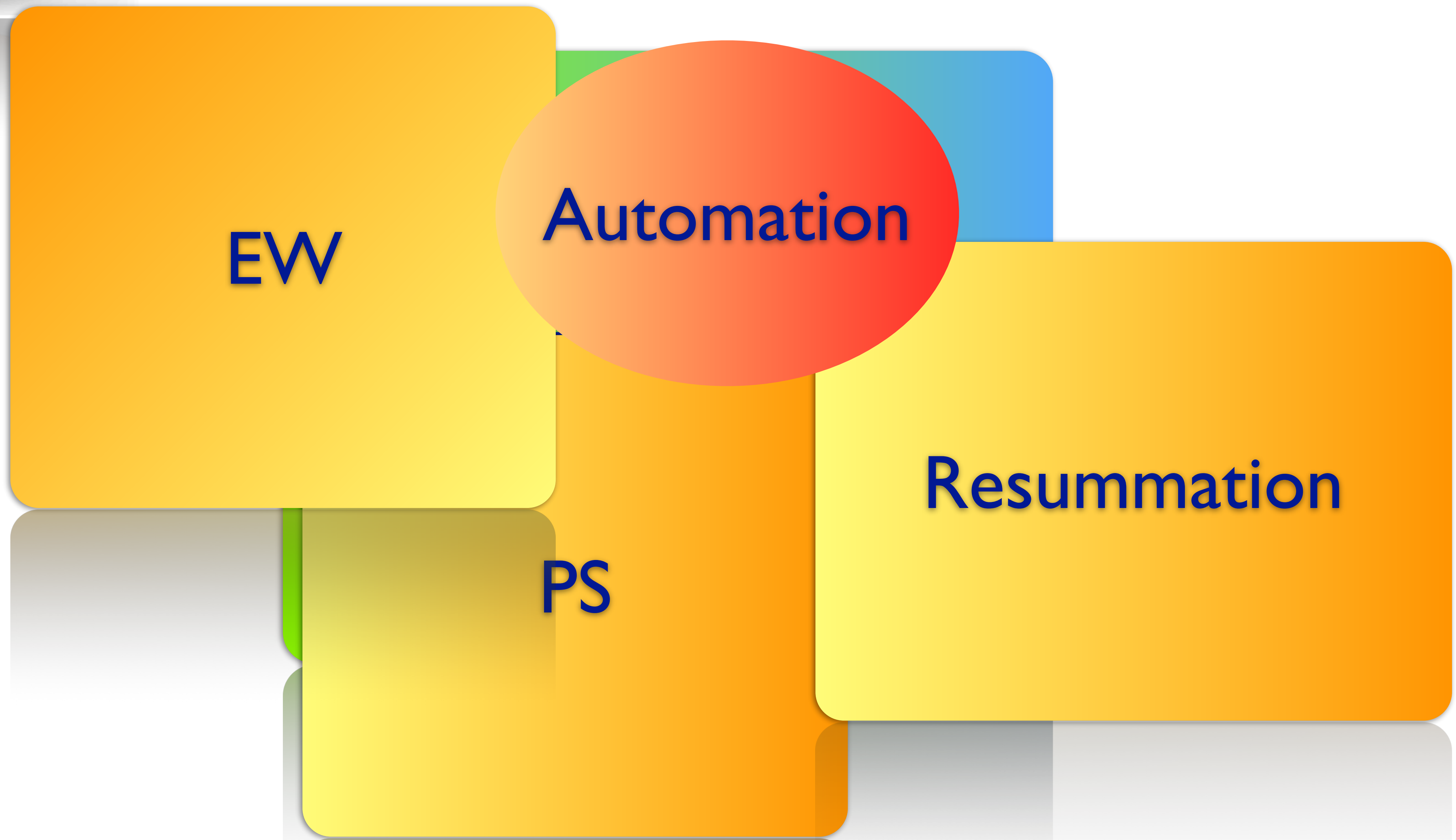
Recommendations for PDF usage in LHC predictions

A. Accardi, S. Alekhin, J. Blümlein, M.V. Garzelli, K. Lipka, W. Melnitchouk, S. Moch, R. Placakyte, J.F. Owens, E. Reya, N. Sato, A. Vogt, O. Zenaiev

(Submitted on 29 Mar 2016)

We review the present status of the determination of parton distribution functions (PDFs) in the light of the precision requirements for the LHC in Run 2 and other future hadron colliders. We provide brief reviews of all currently available PDF sets and use them to compute cross sections for a number of benchmark processes, including Higgs boson production in gluon-gluon fusion at the LHC. We show that the differences in the predictions obtained with the various PDFs are due to particular theory assumptions made in the fits of those PDFs. We discuss PDF uncertainties in the kinematic region covered by the LHC and on averaging procedures for PDFs, such as advocated by the PDF4LHC15 sets, and provide recommendations for the usage of PDF sets for theory predictions at the LHC.

The perturbative toolkit for precision at colliders



The perturbative toolkit for precision at colliders

Everything starts with a fixed order calculation

- Partonic cross-section: expansion in $\alpha_s(\mu_R^2) \ll 1$

$$d\hat{\sigma} = \alpha_s^n \, d\hat{\sigma}^{(0)} + \alpha_s^{n+1} \, d\hat{\sigma}^{(1)} + \ldots$$

Born Cross section

LO : number of tools to compute tree level amplitudes

$$\sigma_{LO} = \int_m |\mathcal{M}^{(0)}(\{p_i\})|^2 \; \mathbf{S} \; (\{p_i\}) d\Phi_m$$

Tree level matrix element — Measurement function — Phase space

- "Brute Force" Feynman Diagrams
- Recursive relations : Berends-Giele, BCFW

Born Cross section

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Fully automated calculations for very large multiplicities

MADGRAPH, HELAC-PHEGAS, ALPGEN, SHERPA, ComHep, COMIX,...

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✓ Born level: simpler to integrate calculation to parton showers

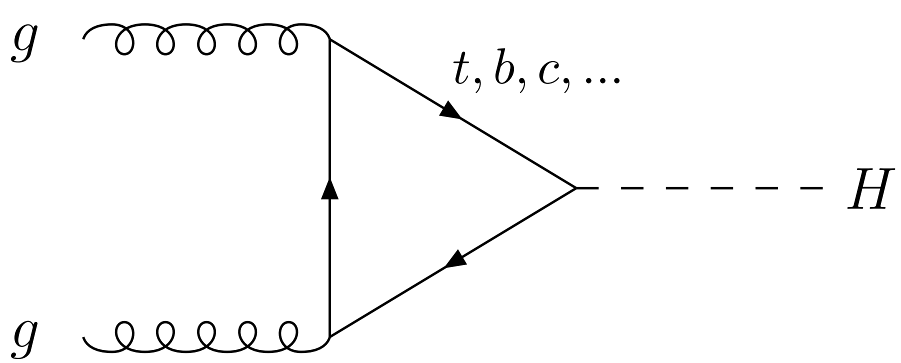
⬇ In most cases, LO not enough for precision physics

Why higher order corrections?

- Large Corrections : check PT
  shape and normalization

$\alpha_s \sim 0.1$ → slow convergence

Higgs production



$$C_0\alpha_s^0 + C_1\alpha_s^1 + C_2\alpha_s^2 + C_3\alpha_s^3 + \ldots$$

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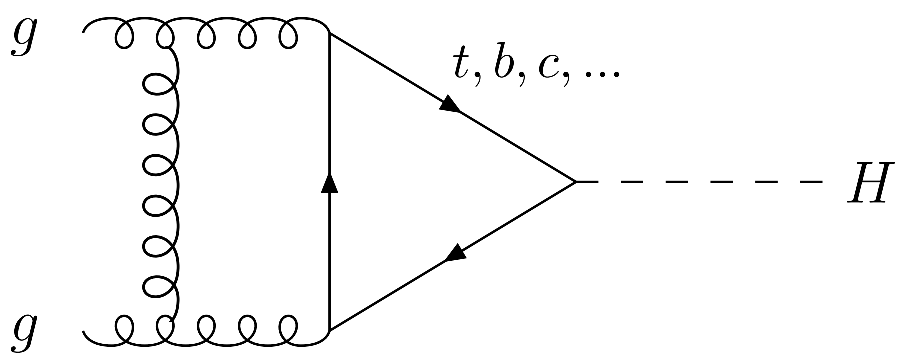

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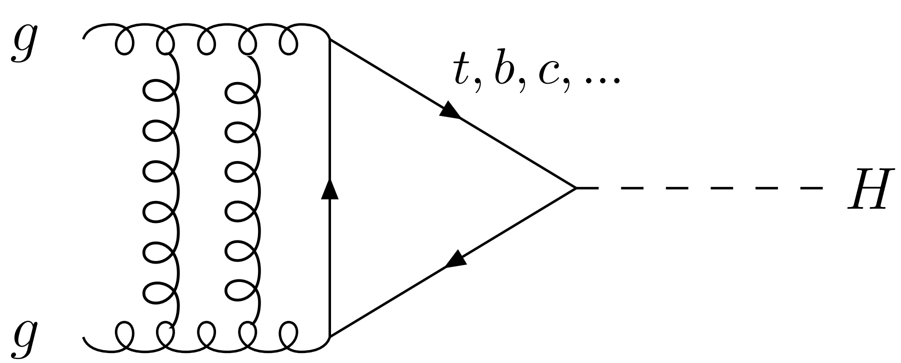

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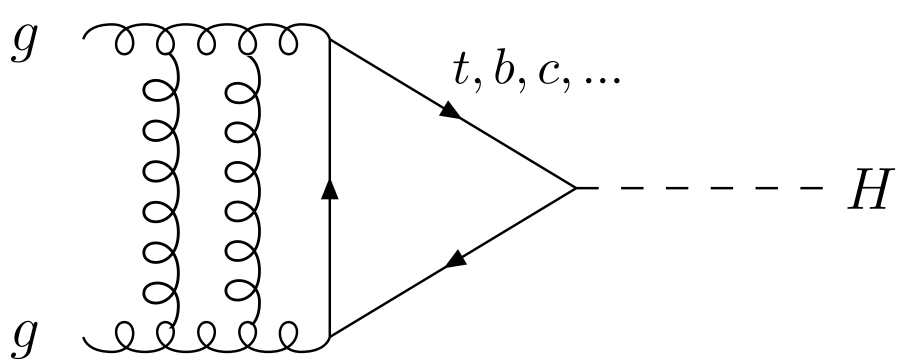

$$C_0\alpha_s^0 + C_1\alpha_s^1 + C_2\alpha_s^2 + C_3\alpha_s^3 + \ldots$$

$$\sigma = \sigma^{(0)}(1 + 0.89 + 0.55 + 0.3 + \ldots)$$

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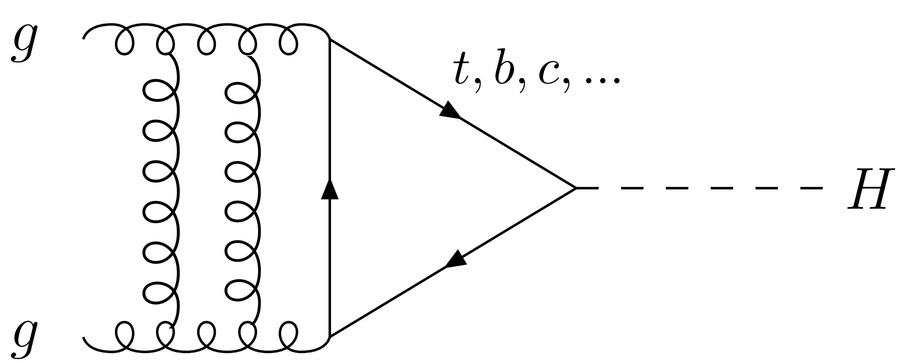
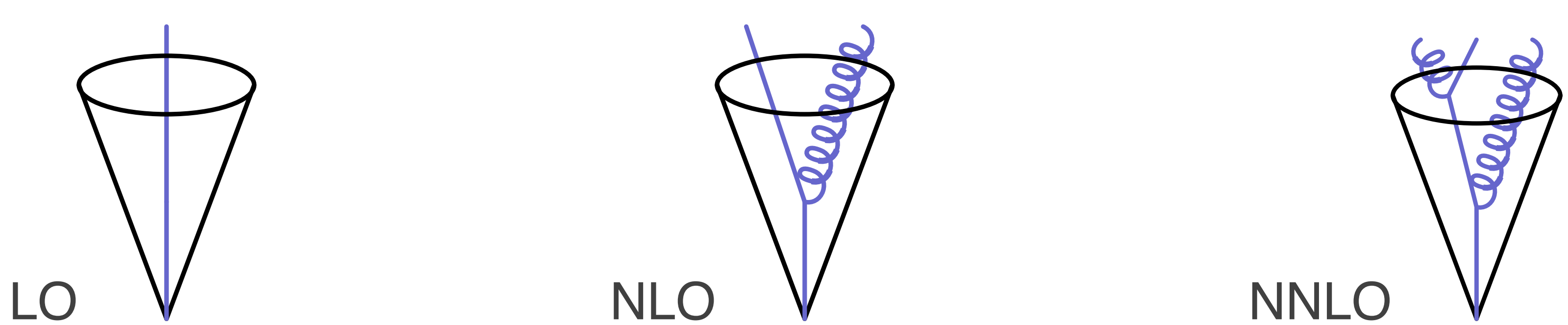


$$C_0 \alpha_s^0 + C_1 \alpha_s^1 + C_2 \alpha_s^2 + C_3 \alpha_s^3 + \ldots$$

$$\sigma = \sigma^{(0)} (1 + 0.89 + 0.55 + 0.3 + \ldots)$$

- Extra radiation : more partons result in better TH/EXP matching



Description of jets, transverse momentum, etc

Accurate Theoretical Predictions

$$\sigma(p_1,p_2) = \sum_{a,b} \int_0^1 dx_1 \int_0^1 dx_2\, f_{a/h_1}(x_1,\mu_F^2)\, f_{b/h_2}(x_2,\mu_F^2) \times \hat{\sigma}_{ab}(x_1 p_1, x_2 p_2, \alpha_s(\mu_R^2), \mu_R^2, \mu_F^2)$$

μ_R Renormalization scale μ_F Factorization scale

- 2 unphysical scales : dependence cancels if computed to all orders
- after "perturbative" truncation: unphysical dependence remains
- (naive) estimate of size of missing higher orders

$$\frac{M_{\mu^+\mu^-}}{2} \leq \mu_F \leq 2 M_{\mu^+\mu^-}$$

$$\frac{M_{\mu^+\mu^-}}{2} \leq \mu_R \leq 2 M_{\mu^+\mu^-}$$

→ TH uncertainty

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$$\sigma(p_1,p_2) = \sum_{a,b} \int_0^1 dx_1 \int_0^1 dx_2\, f_{a/h_1}(x_1,\mu_F^2)\, f_{b/h_2}(x_2,\mu_F^2) \times \hat{\sigma}_{ab}(x_1p_1, x_2p_2, \alpha_s(\mu_R^2), \mu_R^2, \mu_F^2)$$

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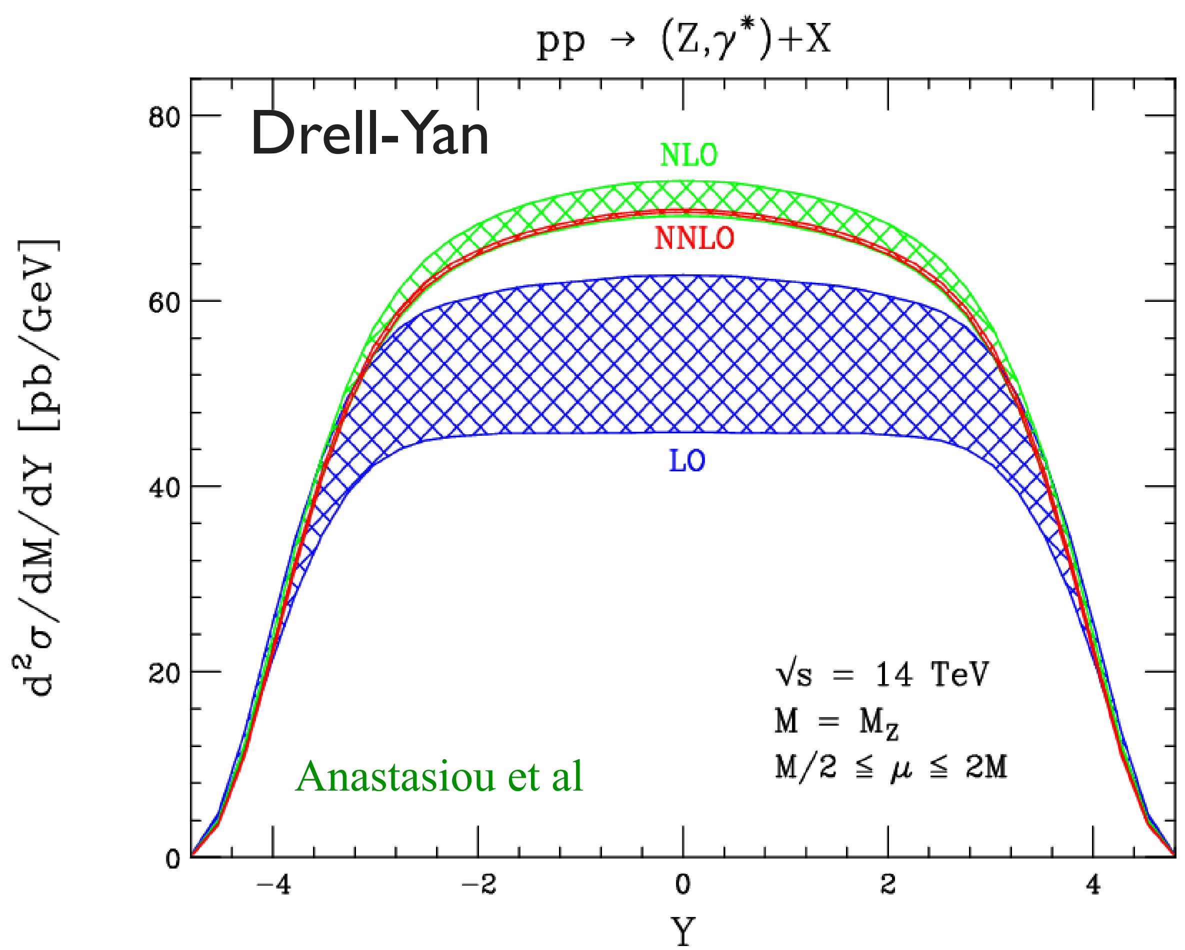
- (naive) estimate of size of missing higher orders

$$\frac{M_{\mu^+\mu^-}}{2} \le \mu_F \le 2M_{\mu^+\mu^-}$$

$$\frac{M_{\mu^+\mu^-}}{2} \le \mu_R \le 2M_{\mu^+\mu^-}$$

→ TH uncertainty



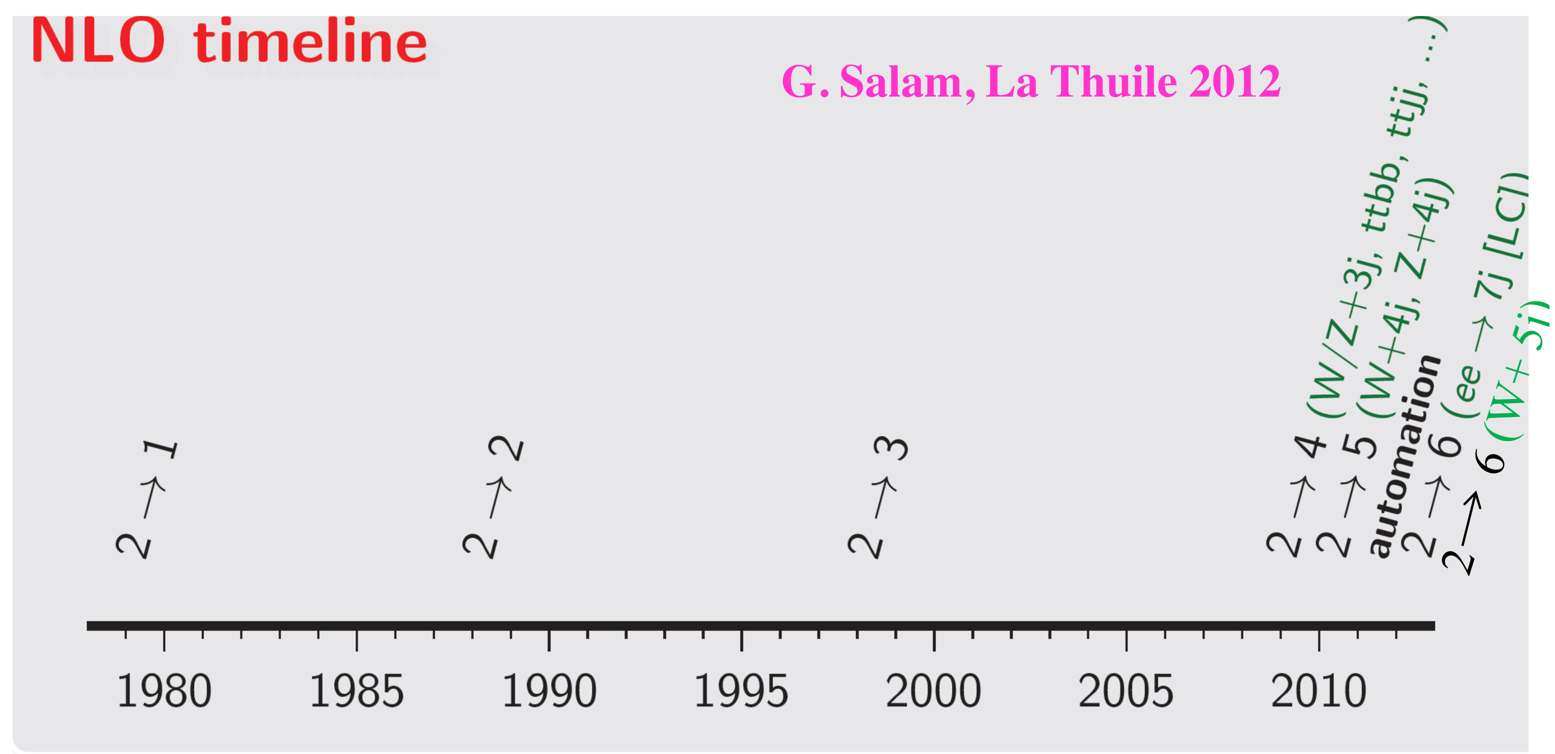
Scale dependence considerably reduced at higher orders

sensible QCD "starts" at NLO

2?

NLO

The NLO revolution



Why so complicated?

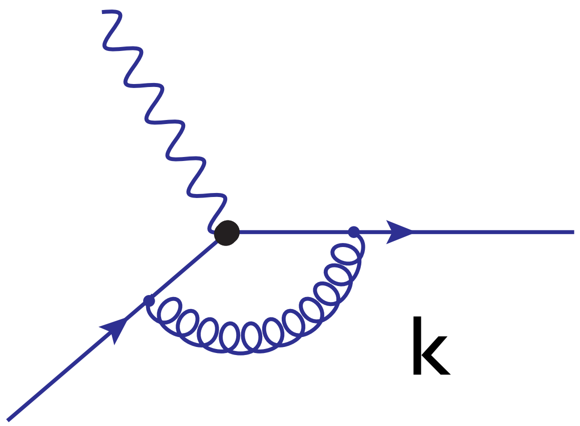
Blame Feynman!

- Real and virtual contributions : separately divergent

UV

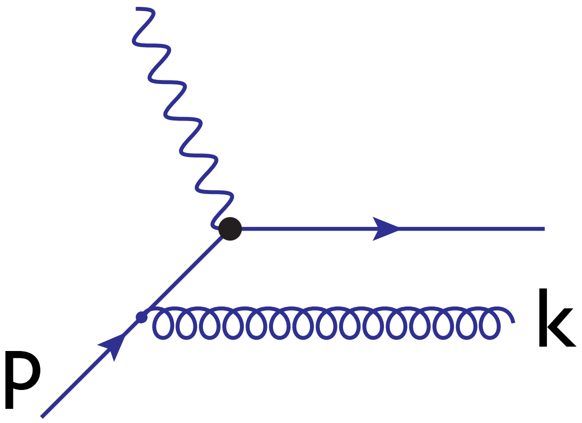
$$\int_0^\infty dk$$

IR



+

$$\int dk$$



1 loop

$$\frac{-1}{(p-k)^2} = \frac{1}{2\,p \cdot k} = \frac{1}{2E_q E_g (1-\cos\theta)}$$

dimensional regularization $\rightarrow$ $\frac{1}{\epsilon^2}$

$\epsilon = d - 4$

1 extra parton

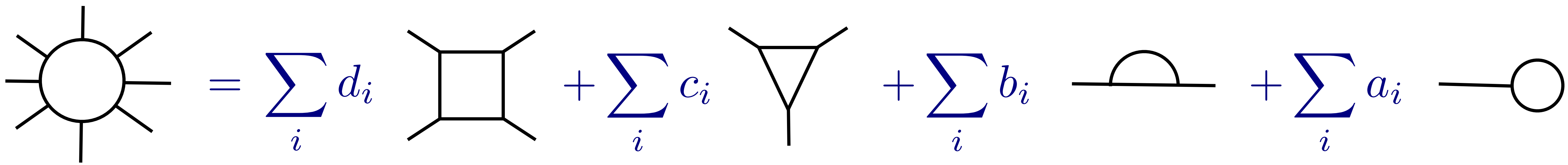
IR in soft/collinear configurations

- Real contribution : singularity, integration, subtraction

- Virtual contribution : technical problems (large multiplicities)

Revolution in calculation of 1-loop amplitudes

- Bottleneck was in the virtual contribution : large multiplicities

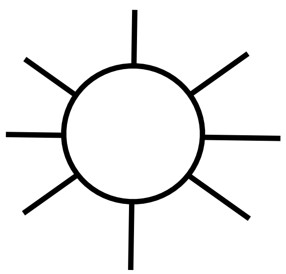


Decomposition and reduction involved (all integrals known!)

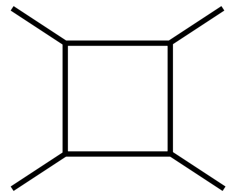
- Large number of diagrams (>1000)
- Growing number of terms in tensor reduction
- Numerical stability : vanishing of Gram determinant

Revolution in calculation of 1-loop amplitudes

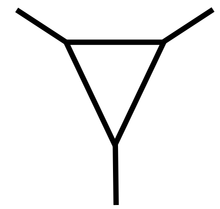
- Bottleneck was in the virtual contribution : large multiplicities



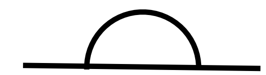
$= \sum_i d_i$



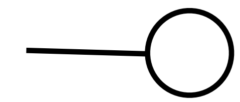
$+ \sum_i c_i$



$+ \sum_i b_i$



$+ \sum_i a_i$



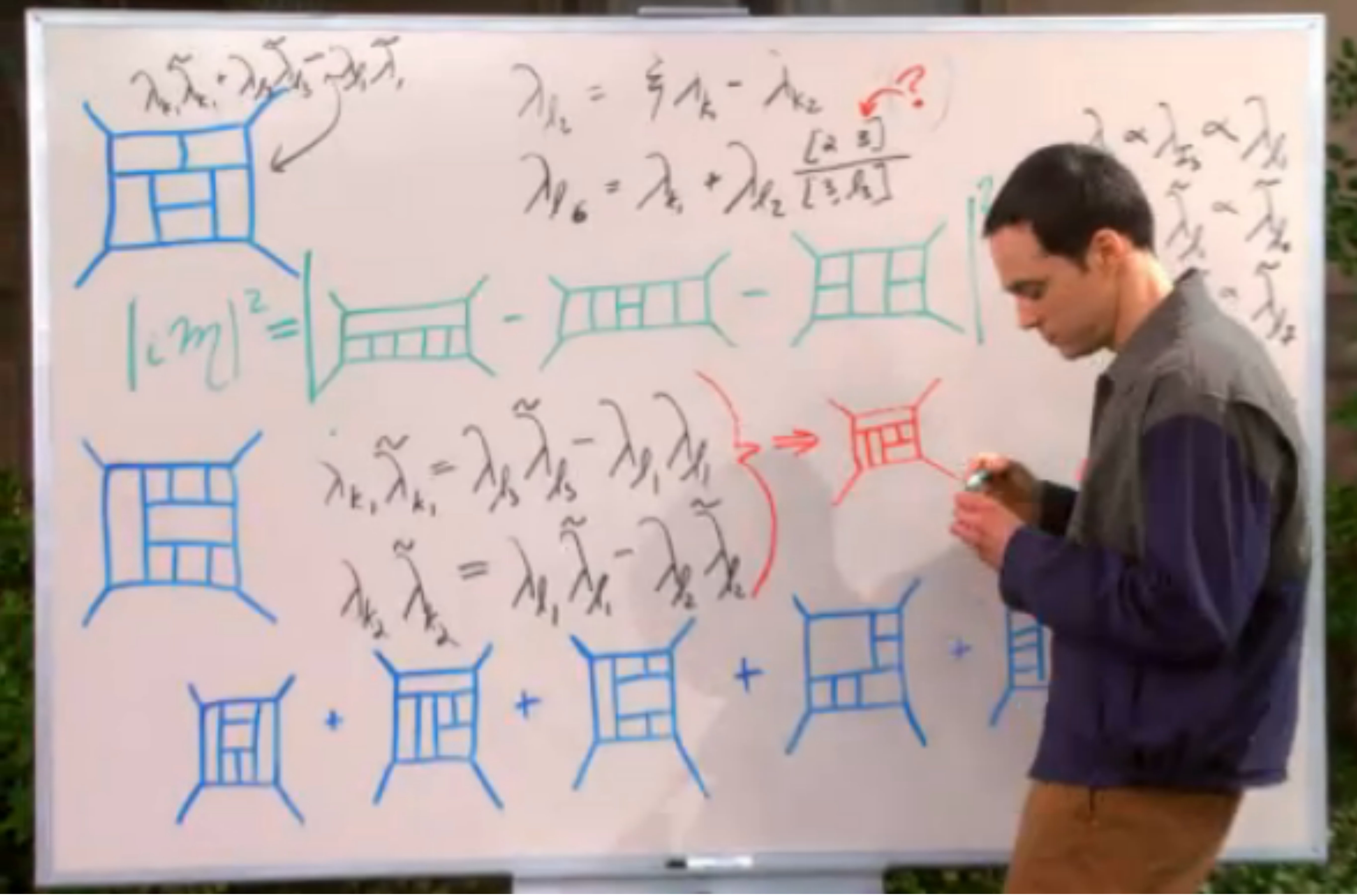
Decomposition and reduction involved (all integrals known!)

- Large number of diagrams (>1000)
- Growing number of terms in tensor reduction
- Numerical stability : vanishing of Gram determinant

- Feynmanian approach Improvements in decomposition and reduction

- Unitarian approach Use multi-particle cuts from generalized unitarity

OPP Ossola, Papadopoulos, Pittau
decomposition at the integrand level → "algebraic problem"



- Final goal: Really automatic NLO calculations

zero cost for humans

- Automatic NLO calculation "conceptually" solved
  - in a few years a number of codes

HELAC-NLO, Rocket, BlackHat+SHERPA, GoSam+SHERPA/MADGRAPH, NJet+SHERPA, Madgraph5-aMC@NLO, RECOLA, OpenLoops+SHERPA

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How easy is NLO these days?

```
import model loop_sm-no_b_mass
define p = g u u~ c c~ d d~ s s~ b b~
define j = g u u~ c c~ d d~ s s~ b b~
generate p p > t~ t j [QCD]
output my_pp_ttj
calculate_xs NLO
```

$pp \to tt+j$

e.g. MadGraph5_aMC@NLO v2.1.1
[Alwall et al. 1405.0301]

generation time ~ 5 mins

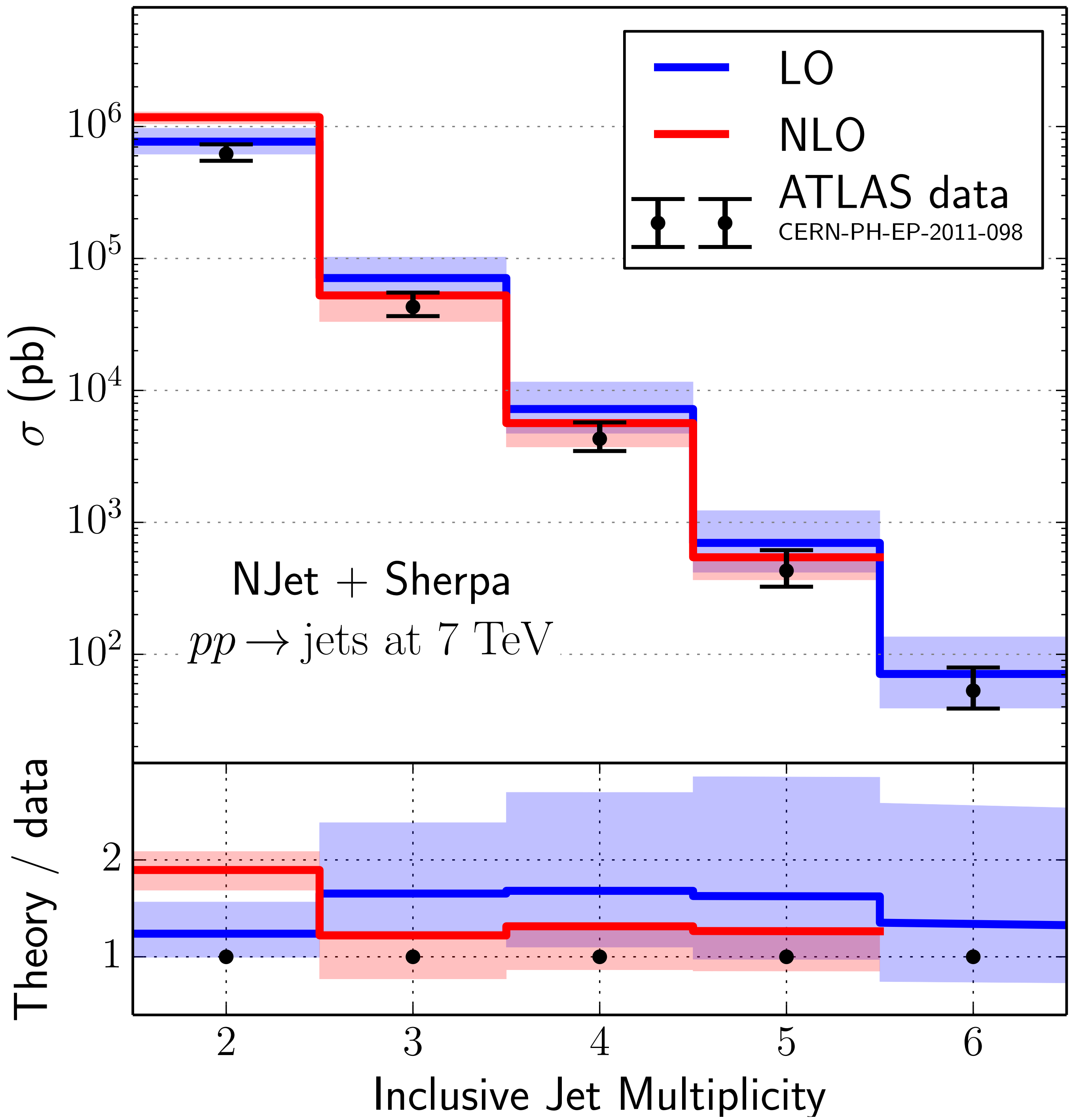
total cross section ~ 30 mins (20 cores)

- Still limitations in numerical accuracy for processes with many particles (>4) in final state

Multi-jet production

$pp \to 5\,\text{jets at NLO}$

Njet+Sherpa (Badger, Biedermann, Uwer, Yundin)



- NLO in very good agreement with data!

- Better stability

$$\widehat{H}_T = \sum_{i=1}^{N_{\text{parton}}} p_{T,i}^{\text{parton}}$$

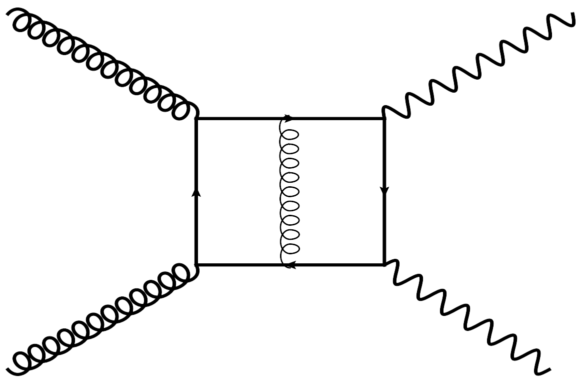
- Not everything solved at NLO yet… but constant progress

- Parton Showers @NLO

- Automated EW corrections MADGRAPH5_AMC@NLO Sherpa+Recola

  - QCD dominant (except very large pT)
  - Coupling hierarchy ~ respected
  - Large cancellations in EW contributions

- Loop induced Processes $gg \to VV$



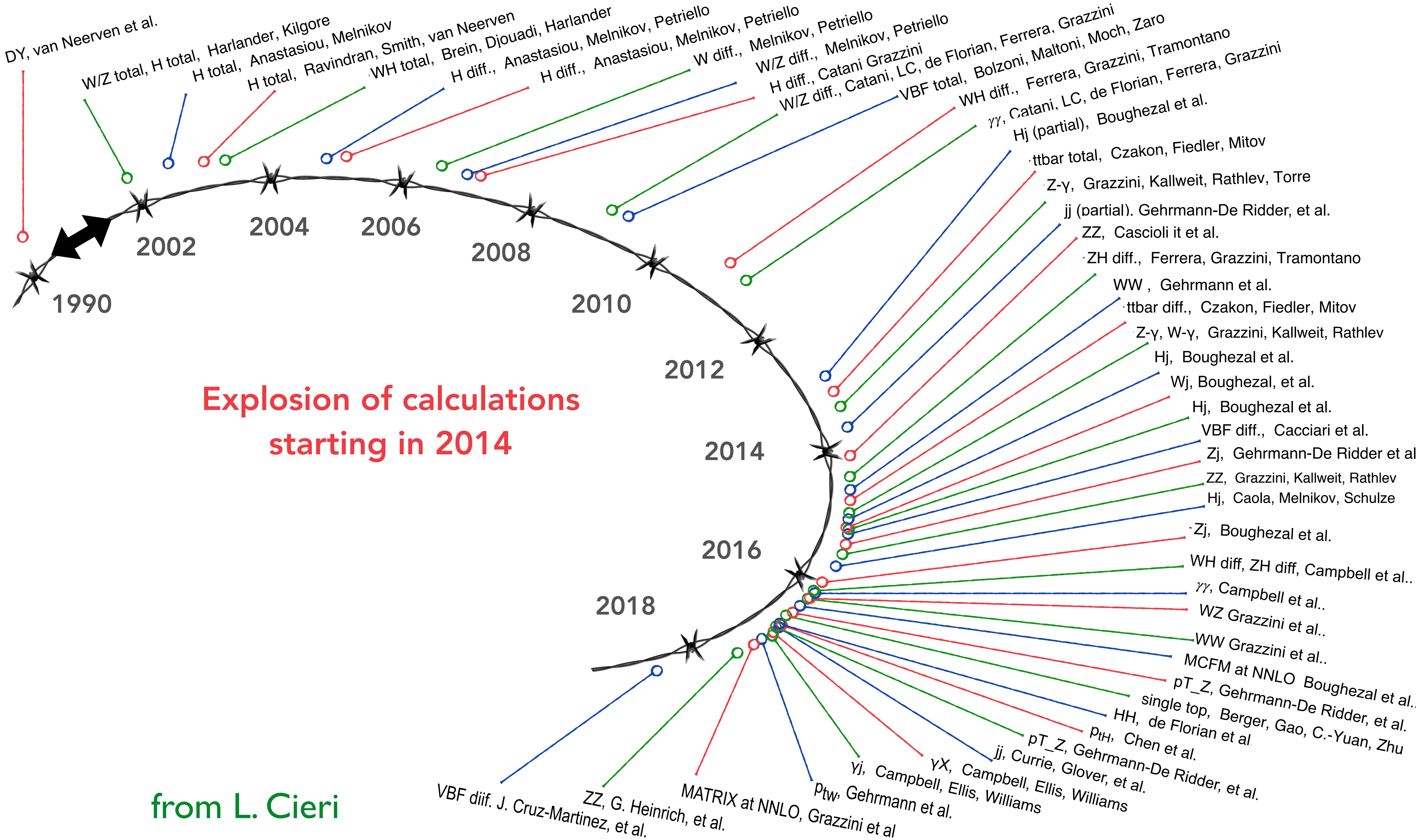
- Enhanced by gluon luminosity
- Corrections for gg channel usually large (color, logs)

F. Caola, et al (2015-2016)
J. Campbell, K. Ellis, M. Czakon, S. Kirchner (2015)

- BSM (arbitrary, higher dimensional operators, etc)

~Automated! BSM@NLO+aMC@NLO
MadGolem

The NNLO revolution

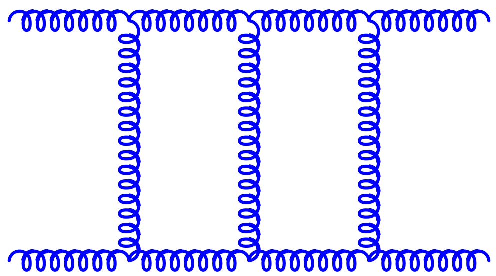


Explosion of calculations starting in 2014

from L. Cieri

Degree of complexity at NNLO

- 2 loop

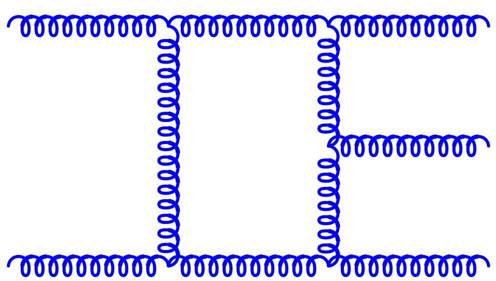


loop integrals → explicit infrared poles $\frac{1}{\epsilon^4}$

$2 \to 2$ available (even for VV production)

- Bottleneck for larger multiplicities?

- 1 loop + single emission

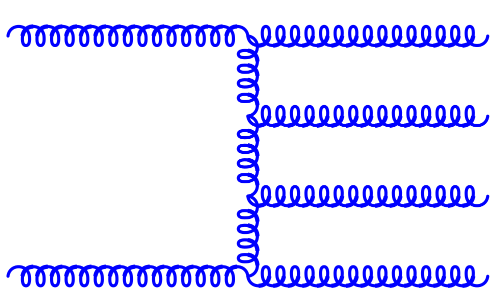


"NLO complexity" : loop → $\frac{1}{\epsilon^2}$

singular emission → $\frac{1}{\epsilon^2}$

- Double real emission

Tree level Trivial to compute Amplitudes
a Hell of infrared singularities



- Bottleneck for larger multiplicities?

after integration over unresolved partons → $\frac{1}{\epsilon^4}$ poles

different approaches to deal with divergences

Sector decomposition
Anastasiou, Melnikov, Petriello; Binoth, Heinrich

Antennae subtraction
Gehrmann, Gehrmann-de Ridder, Glover

Sector-Improved residue subtraction
Czakon, Boughezal, Melnikov, Petriello

CoLorFul subtraction
Del Duca, Somogyi, Trocsanyi

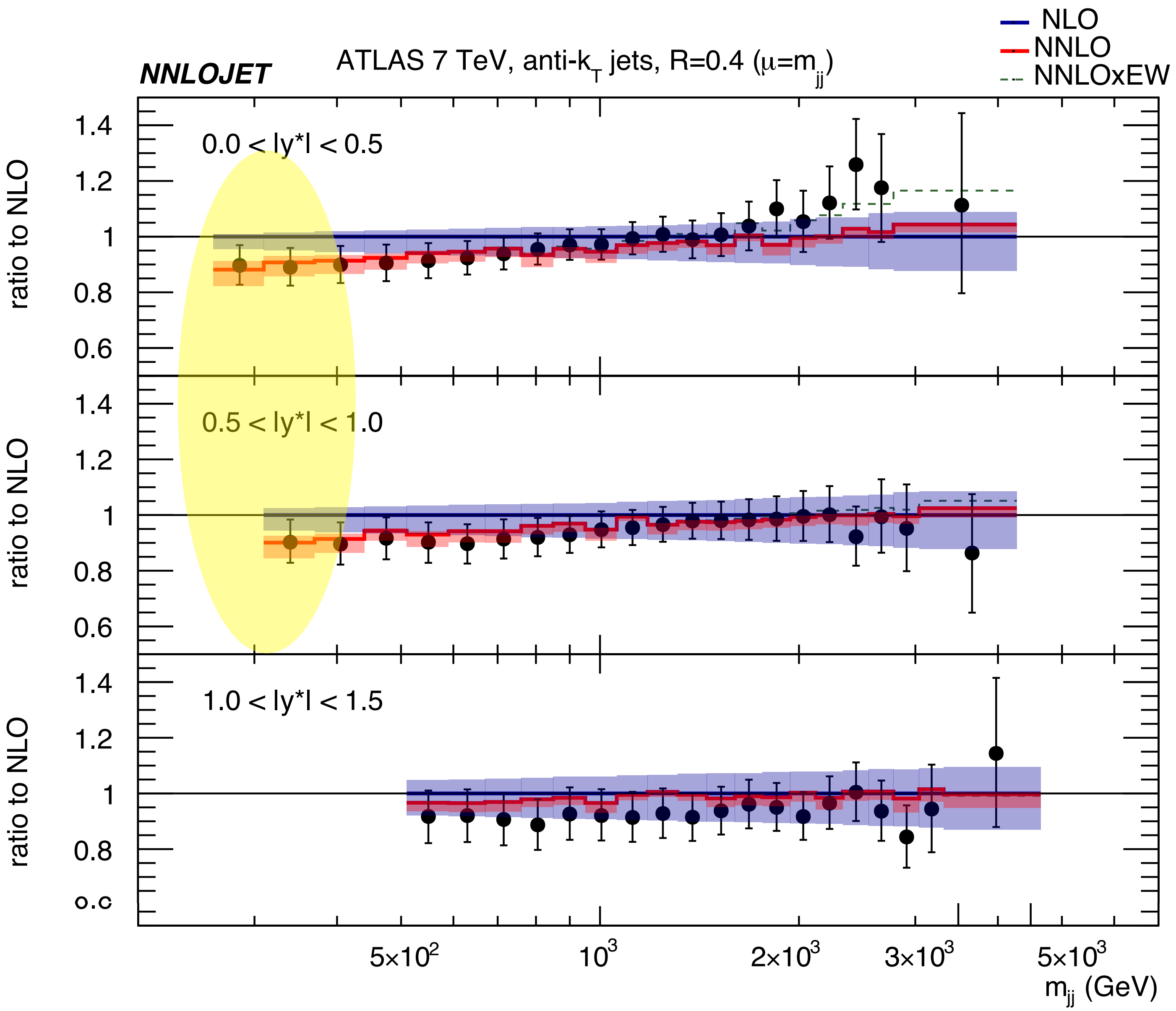
Projection-to-Born
Cacciari, Dreyer, Karlberg, Salam, Zanderighi

q_T-subtraction
Catani, Grazzini; Catani, Cieri, deF, Ferrera, Grazzini

N-jettiness subtraction
Boughezal, Focke, Liu, Petriello;
Gaunt, Stahlhofen, Tackmann, Walsh

$pp \to 2\,\text{jets}$

- Leading color using antenna subtraction : NNLOJET (1 and 2 jets)



J.Currie, E.W.N. Glover, J.Pires (2016)

J.Currie et al (2017)

- NNLO scale dep. < EXP errors
- NLO underestimates uncertainty

- Moderate NNLO corrections (<10%)
- Improve description of data for low M_{jj}/y^*
- Invariant mass natural scale (better convergence)
- Cures pathological NLO behavior for $\langle p_T \rangle$

$$\mu = m_{jj}$$

$$\mu = \frac{1}{2}(p_{T_1} + p_{T_2})$$

Towards automation @ NNLO

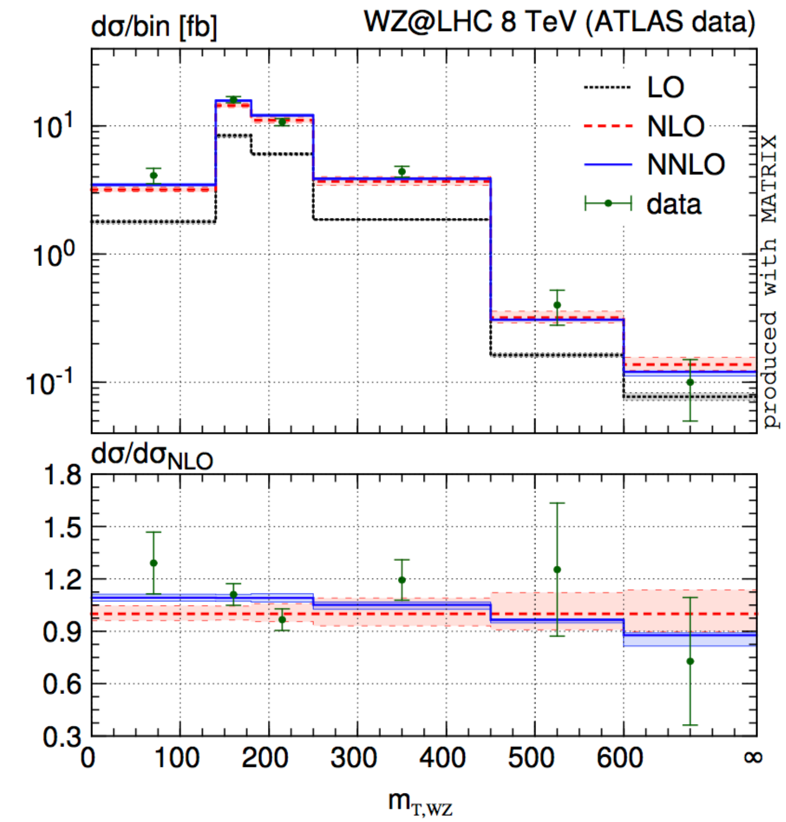
Matrix @ NNLO

M. Grazzini, S. Kallweit, D. Rathlev, M. Wiesemann (2016)

- pp→Z/γ* (→l+l-) ✅
- pp→W(→lν) (✅)
- pp→H ✅
- pp→γγ ✅
- pp→Wγ→lνγ ✅
- pp→Zγ→l+l-γ ✅
- pp→ZZ(→4l) ✅
- pp→WW →(lνl'ν') ✅
- pp→ZZ/WW →llνν ✅
- pp→WZ →lνll ✅
- pp→HH (✅)

▸ NNLO parton level generator with several processes in unique framework (di-boson)

- qt subtraction
- Open-Loops : X+1 parton
- Will include qT resummation
- So far, colored singlet final state
- Public version available



Towards automation @ NNLO

Matrix @ NNLO

M. Grazzini, S. Kallweit, D. Rathlev, M. Wiesemann (2016)

- $pp \to Z/\gamma^*$ $(\to l^+l^-)$ ✅
- $pp \to W(\to l\nu)$ (✅)
- $pp \to H$ ✅
- $pp \to \gamma\gamma$ ✅
- $pp \to W\gamma \to l\nu\gamma$ ✅
- $pp \to Z\gamma \to l^+l^-\gamma$ ✅
- $pp \to ZZ(\to 4l)$ ✅
- $pp \to WW \to (l\nu l'\nu')$ ✅
- $pp \to ZZ/WW \to ll\nu\nu$ ✅
- $pp \to WZ \to l\nu ll$ ✅
- $pp \to HH$ (✅)

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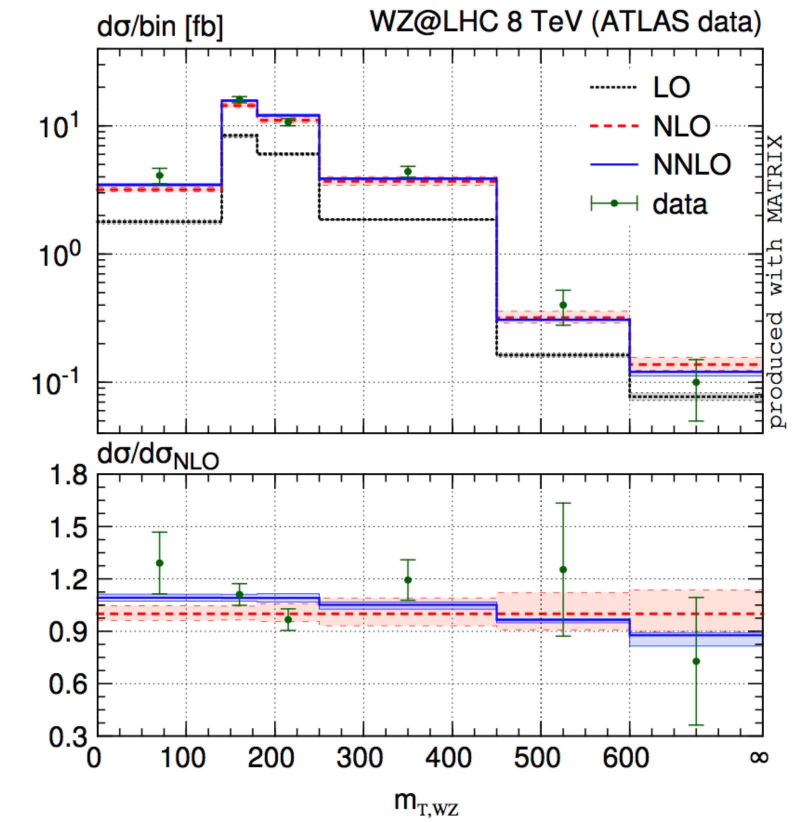


MCFM@ NNLO

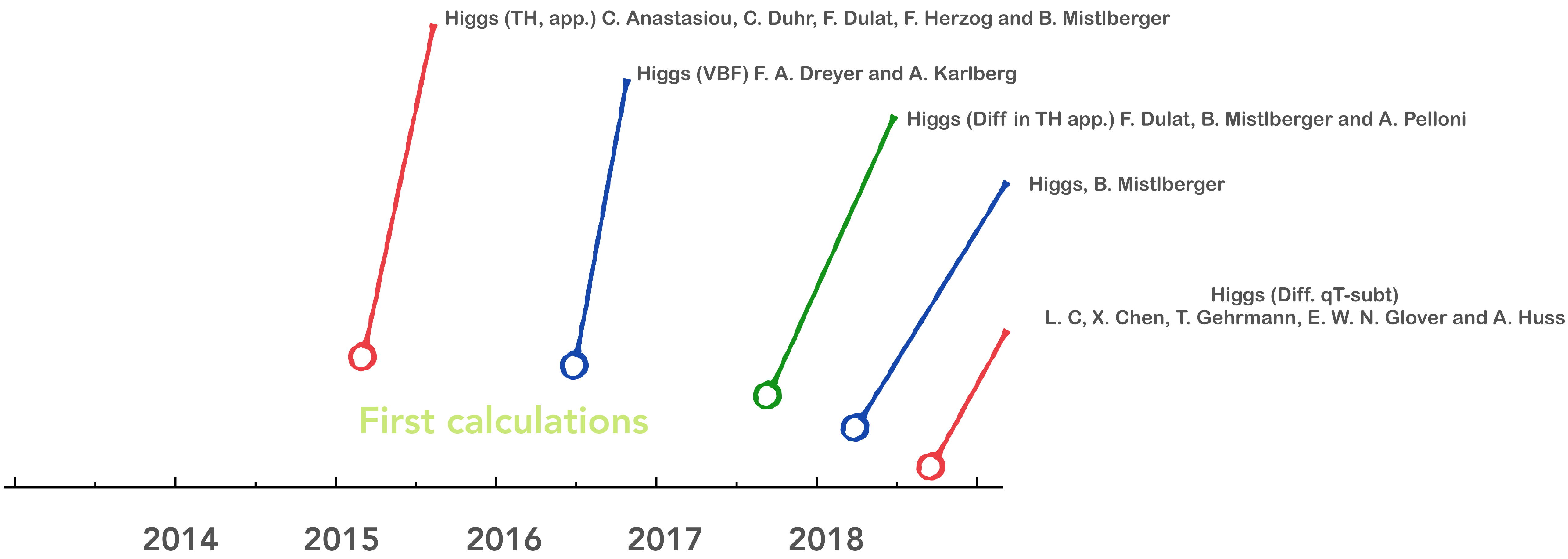
R. Boughezal, J. Campbell, K. Ellis, C. Focke, W. Giele, X. Liu, F. Petriello(2016)
J. Campbell, T.Neumann, C.Williams (2017)

- N-Jettiness
- Less processes available yet : V+1 jet done

W^+
W^-
Z
H
$\gamma\gamma$ $Z\gamma$
W^+H
W^-H
ZH

N^{3}LO

The new Frontier?

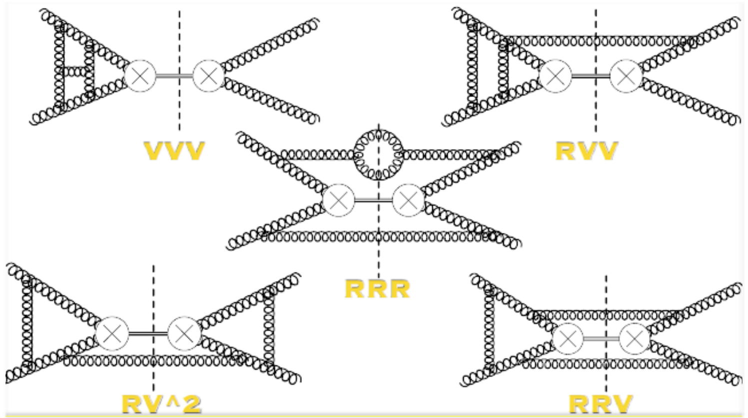


from L. Cieri

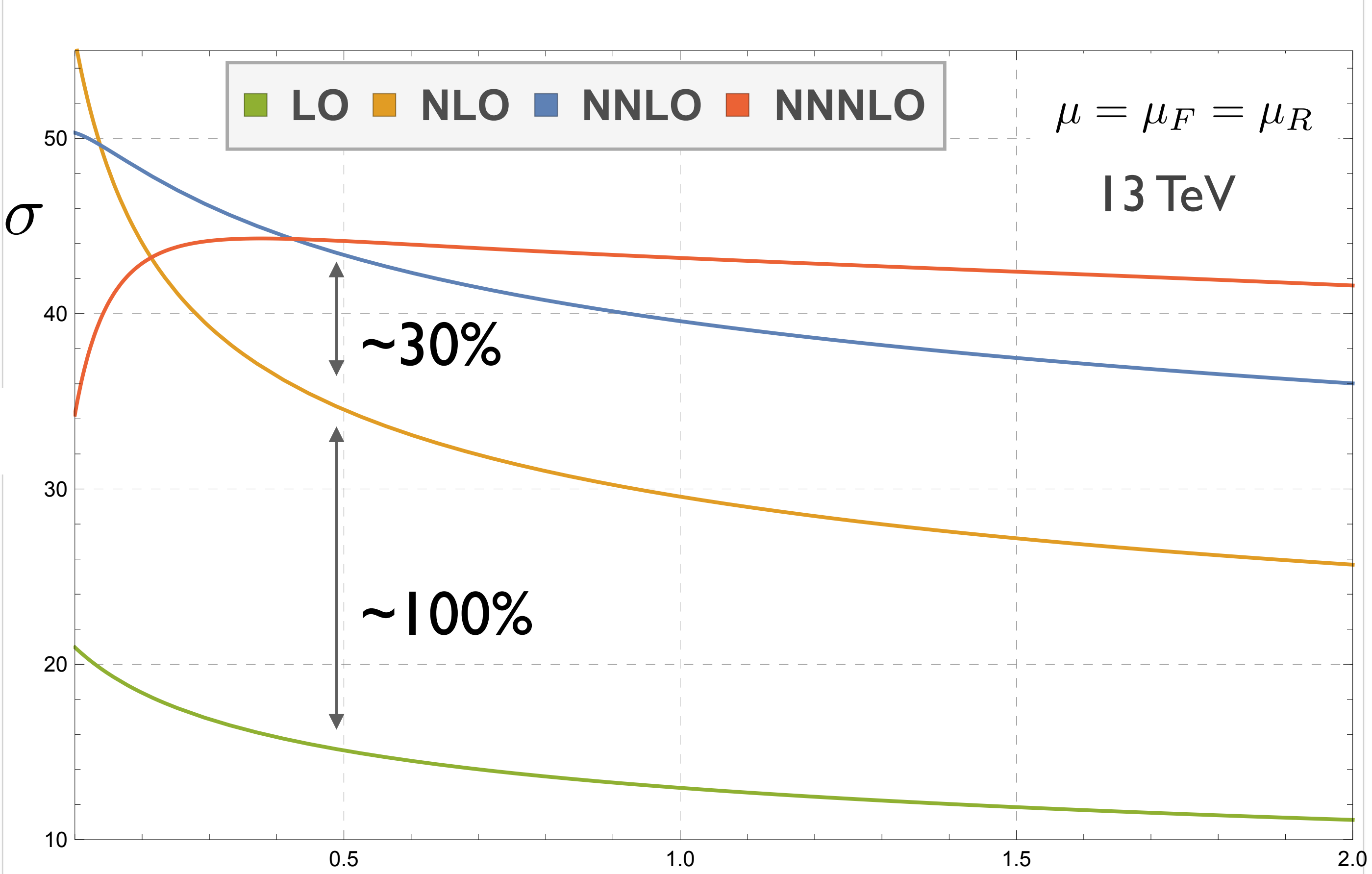
Higgs at N^3LO

C. Anastasiou, C. Duhr, F. Dulat, F. Herzog, B. Mistlberger (2015)
B. Mistlberger (2018)

- Very relevant observable called for higher orders (slow convergence)
- Impressive calculation : new techniques
  - Within (excellent) heavy top approximation



68273802 loop and
phase space integrals



- Observe stabilization of expansion
- Small correction (2% at $M_H/2$)
- Scale variation at N^3LO ~2%

N³LO Splitting functions

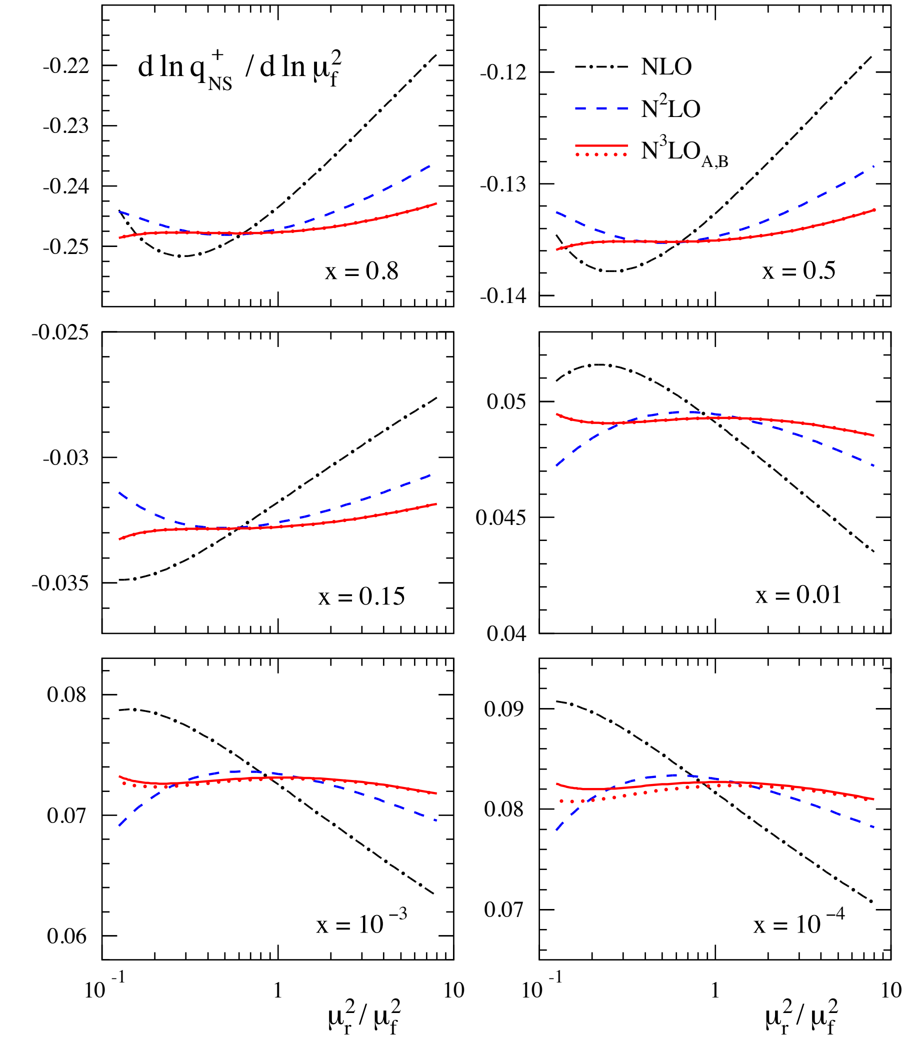
- Non-Singlet 4 loop splitting function

S. Moch, B. Ruijl, T. Ueda, J. Vermaseren, A. Vogt (2017)

- N=20 Mellin moments (large Nc)
- Enough to provide a reconstruction in terms of Harmonic sums
- N=16 beyond large Nc
- Precise for $x \gtrsim 10^{-4}$

$$xq_{\rm ns}^{\pm,{\rm v}}(x,\mu_0^2) \;=\; x^{0.5}(1-x)^3$$

$$\alpha_s(\mu_0^2) \;=\; 0.2$$



- Visible improvement of scale stability

Singlet and Gluon splitting functions feasible

QCD+QED/EW effects

$\mathcal{O}(\alpha) \sim \mathcal{O}(\alpha_s^2)$ suggests NLO EW $\sim$ NNLO QCD and enhanced..

- at high energies
  $\hookrightarrow$ EW Sudakov log's $\propto (\alpha/s_W^2)\ln^2(M_W/Q)$ and subleading log's

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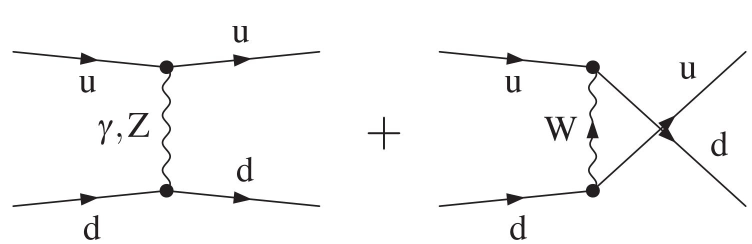
  $\hookrightarrow$ EW Sudakov log's $\propto (\alpha/s_W^2)\ln^2(M_W/Q)$ and subleading log's

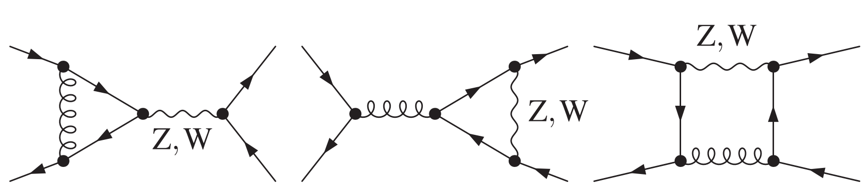
Dijet production

Dittmaier, Huss, Speckner

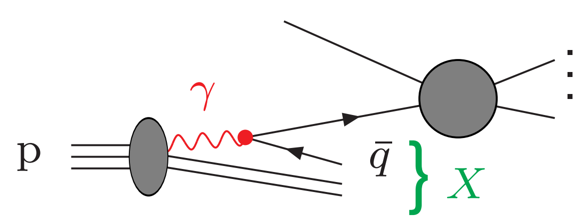
tree EW

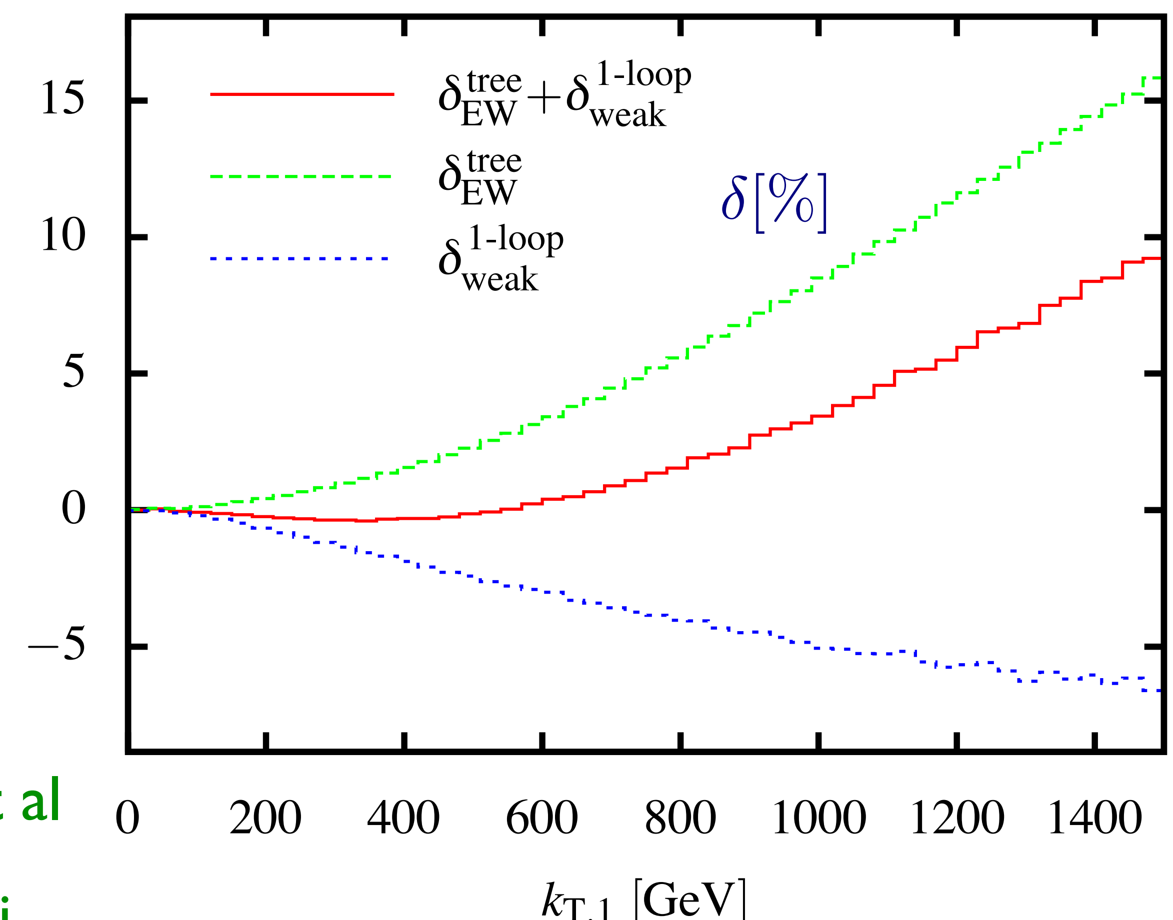


1-loop EW



photon initiated



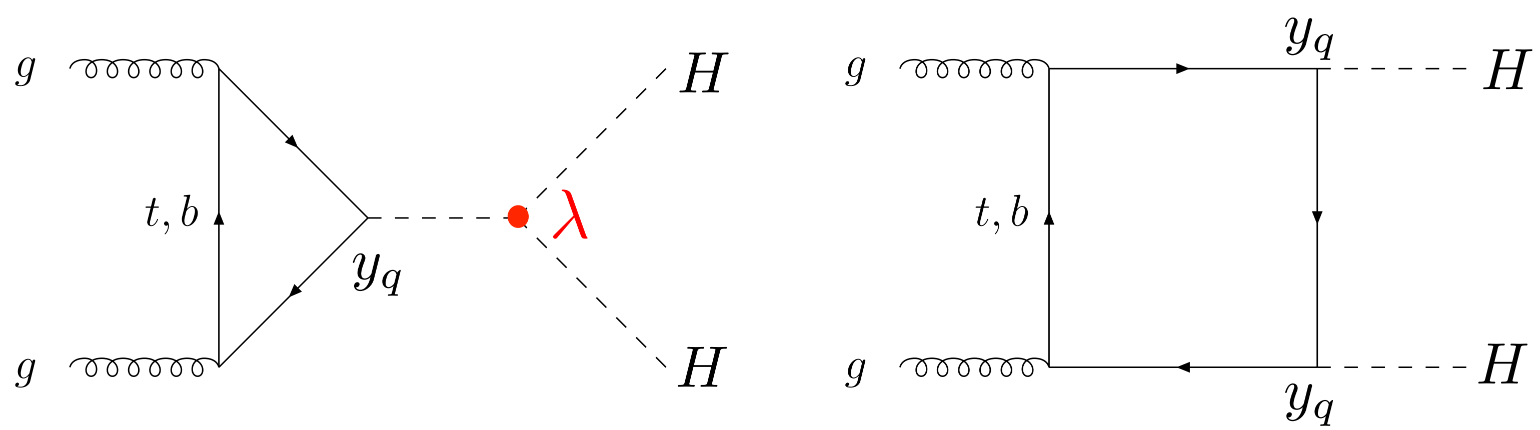


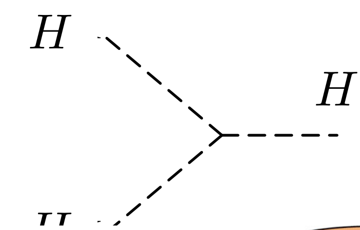
LUXqed :photon content of the proton Manohar et al

QED-QCD splitting functions DdeF, Rodrigo, Sborlini

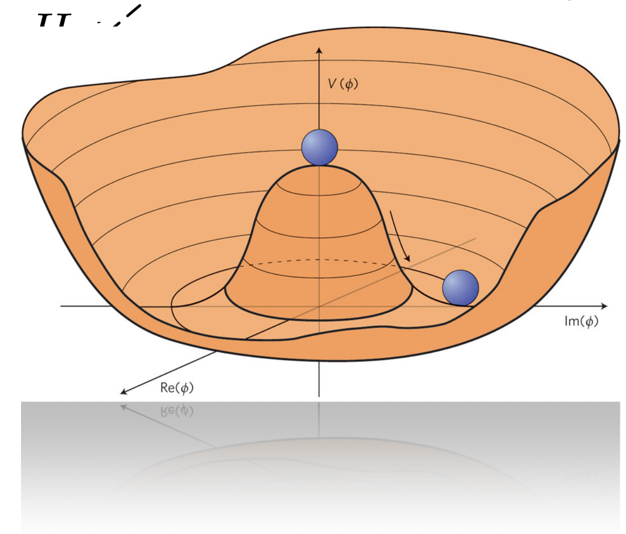
an example : HH production

Two diagrams in the dominant gg fusion channel





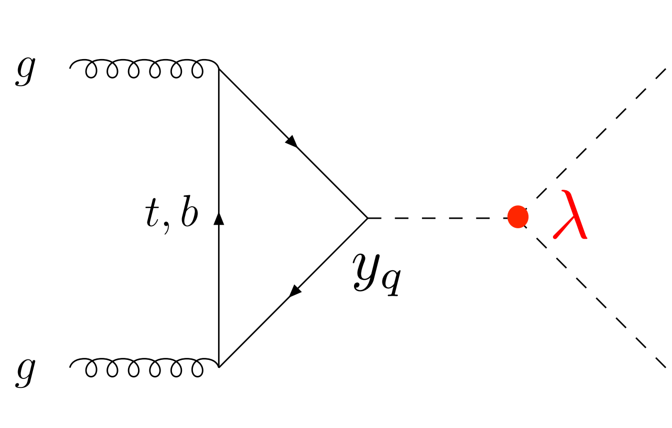
$-3i\frac{m_H^2}{v}$

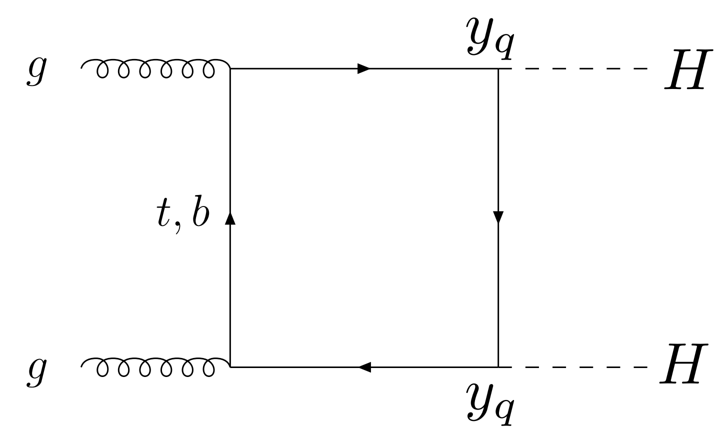


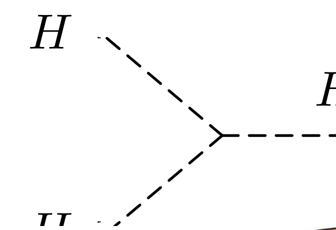
allows to measure directly 3H coupling → explore details of the SSB mechanism

an example : HH production

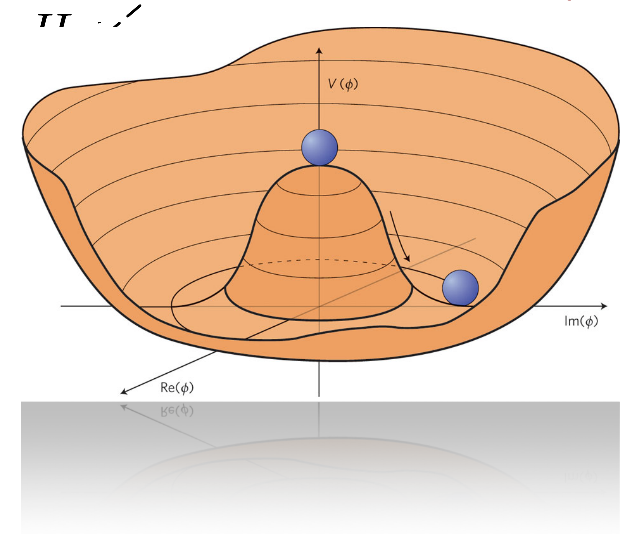
Two diagrams in the dominant gg fusion channel







$$-3i\frac{m_H^2}{v}$$

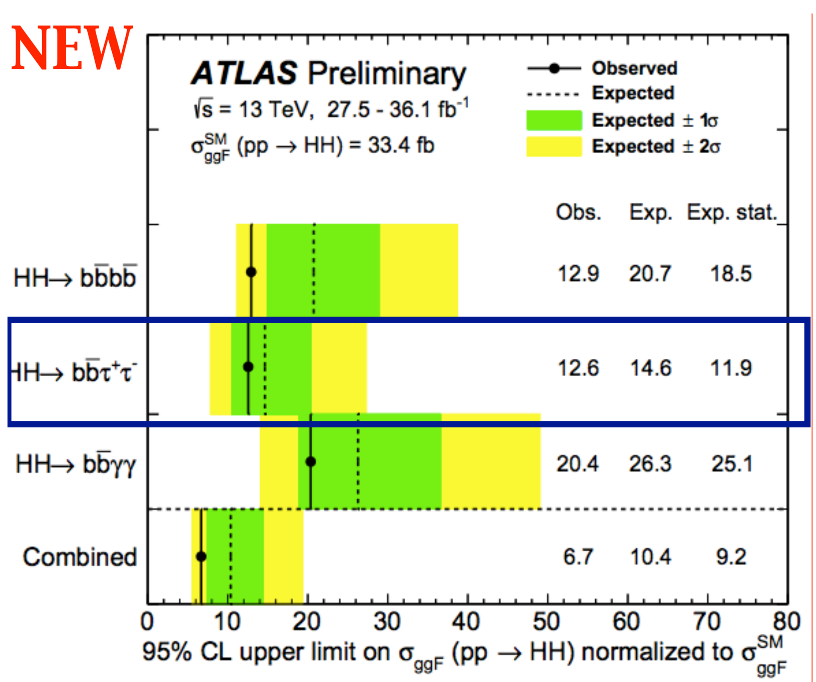


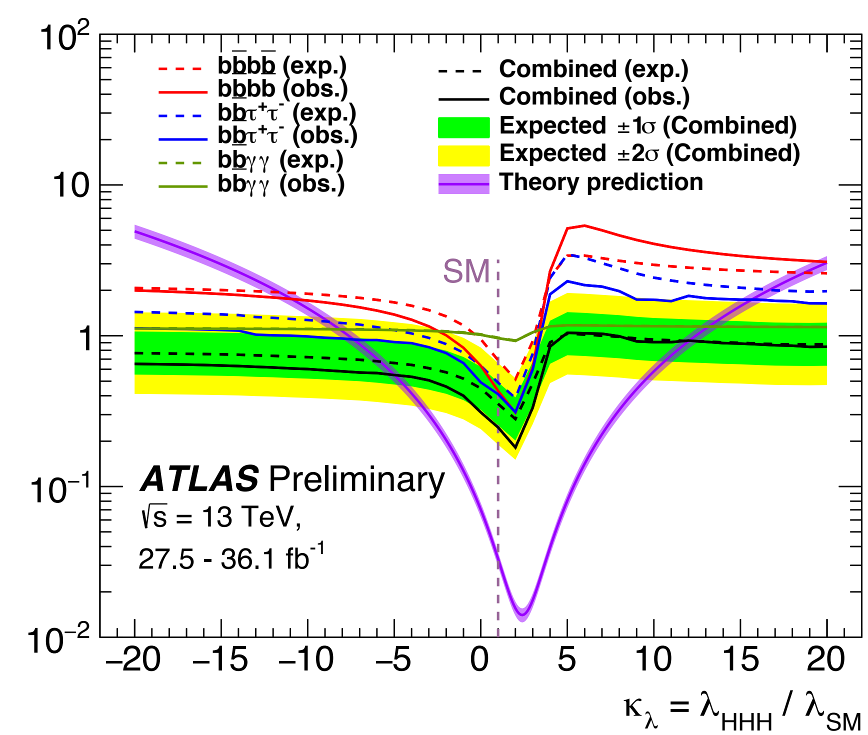
allows to measure directly 3H coupling → explore details of the SSB mechanism

Not yet observed but sensitivity already reaching 10x SM cross-section

$$-5.0 < \kappa_\lambda < 12.1$$

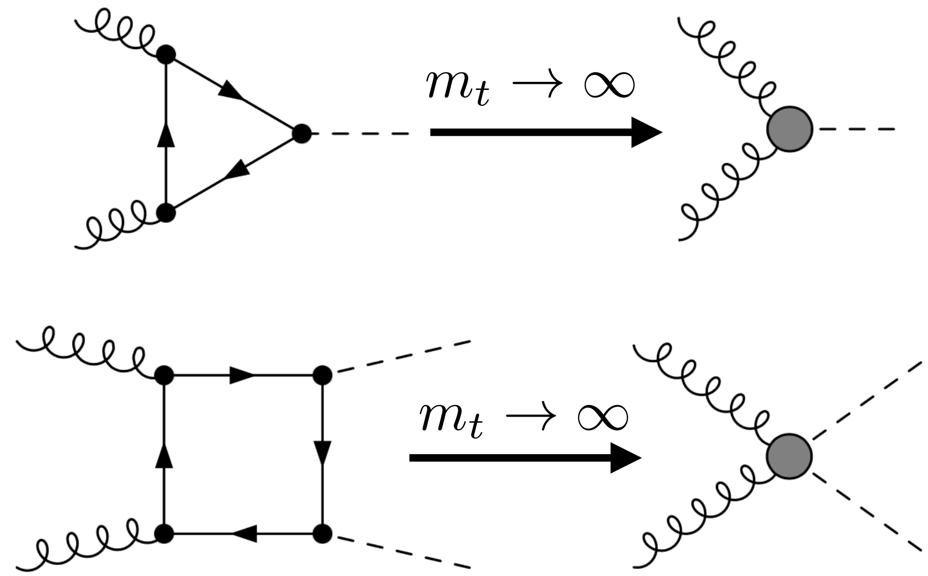
NEW





Processes that start at 1 loop at LO : complicated to reach HO

Customary to rely
on effective field theory



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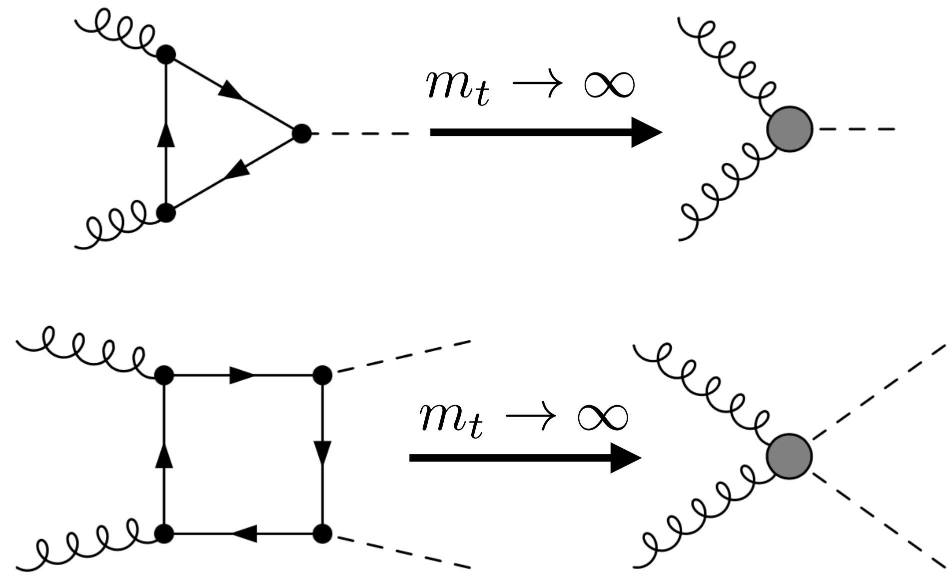
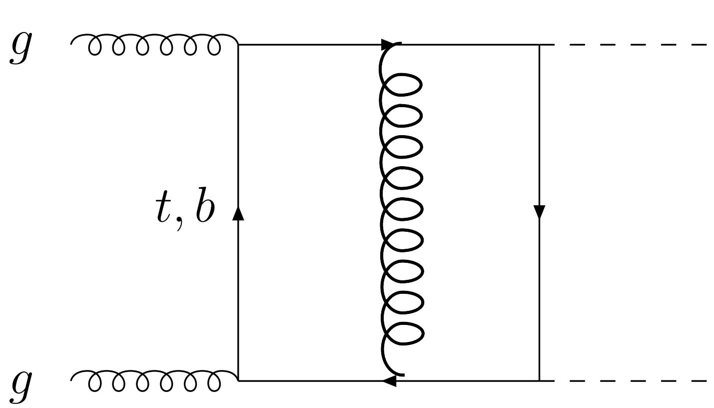
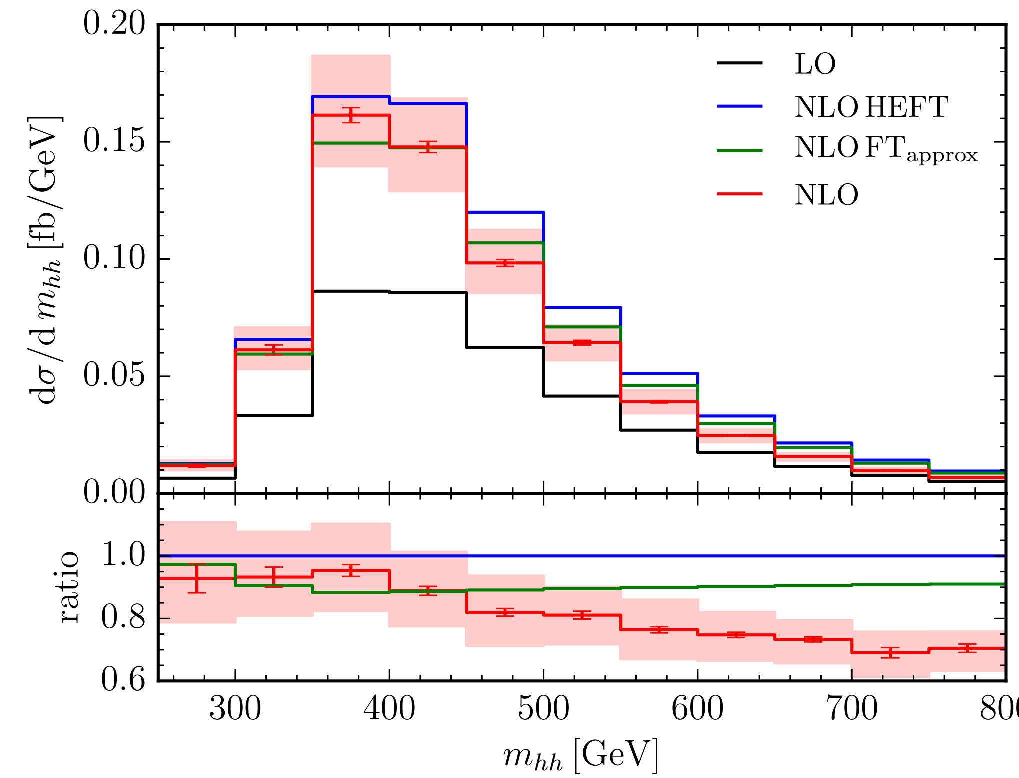


- Full NLO calculation reached very recently
- 2 loop computed numerically
- new techniques

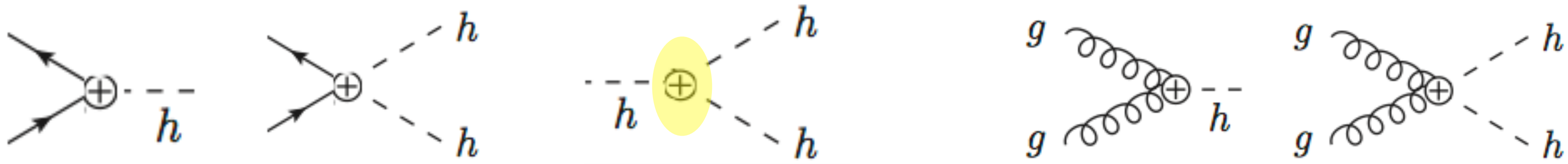
Borowka et al (2016)





Dimension 6 Higgs operators

$$\Delta\mathcal{L}_6 = -m_t\bar{t}t\left(c_t\frac{h}{v}+c_{tt}\frac{h^2}{2v^2}\right)-c_3\frac{1}{6}\left(\frac{3M_h^2}{v}\right)h^3+\frac{\alpha_s}{\pi}G^{a\,\mu\nu}G^a_{\mu\nu}\left(c_g\frac{h}{v}+c_{gg}\frac{h^2}{2v^2}\right)$$



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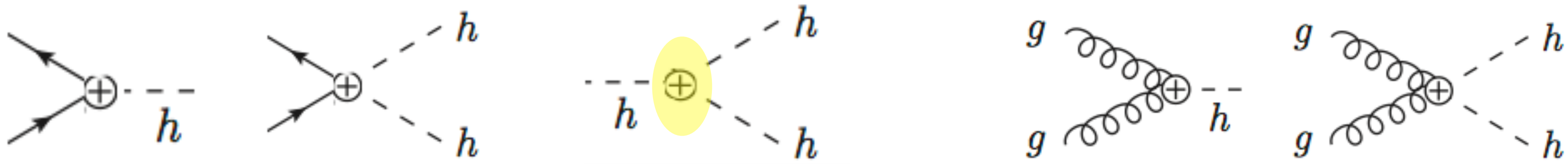
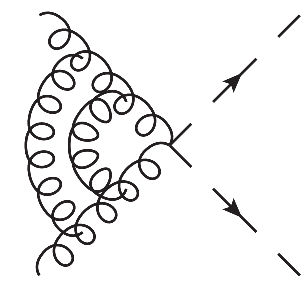


- NNLO available in EFT

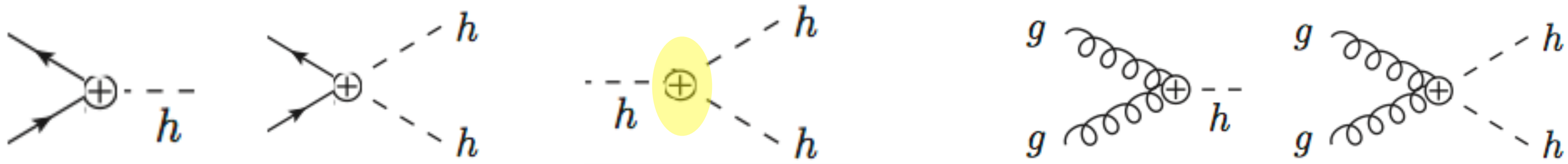
deF, Mazzitelli (2014), deF et al (2016)

QCD corrections non-trivial



Dimension 6 Higgs operators

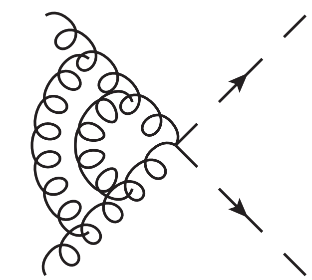
$$\Delta\mathcal{L}_6 = -m_t\bar{t}t\left(c_t\frac{h}{v}+c_{tt}\frac{h^2}{2v^2}\right)-c_3\frac{1}{6}\left(\frac{3M_h^2}{v}\right)h^3+\frac{\alpha_s}{\pi}G^{a\,\mu\nu}G^a_{\mu\nu}\left(c_g\frac{h}{v}+c_{gg}\frac{h^2}{2v^2}\right)$$



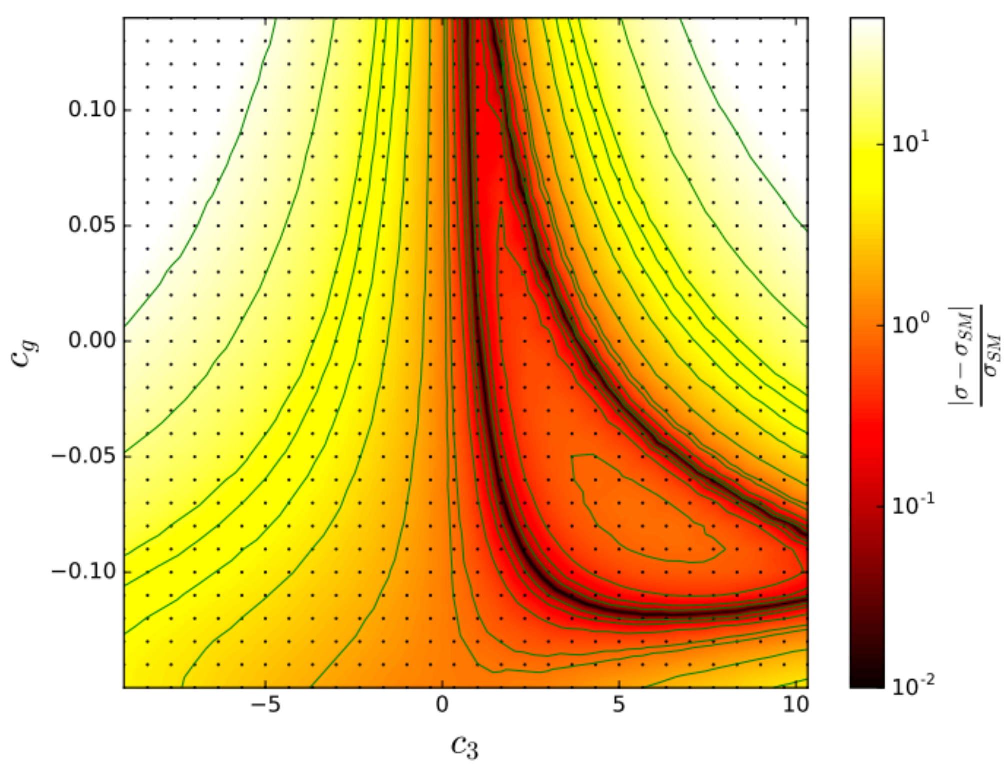
NNLO available in EFT

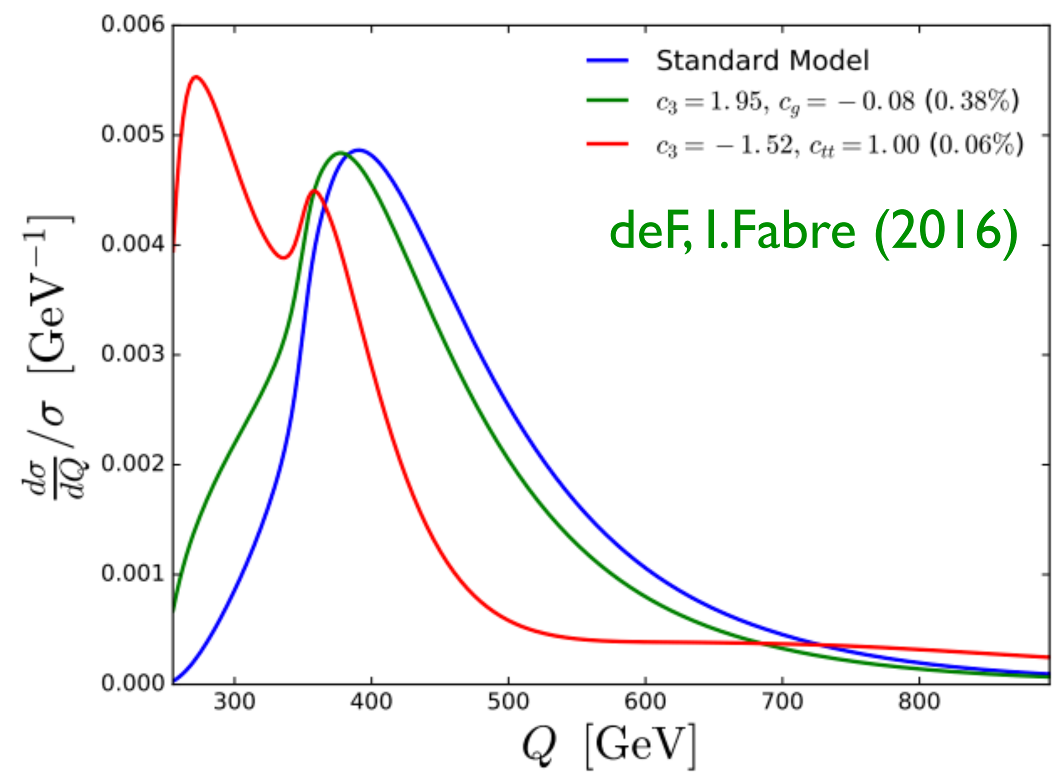
deF, Mazzitelli (2014), deF et al (2016)

QCD corrections non-trivial



- total x-section degeneracy
- broken in invariant mass distribution





Conclusions

- Amazing progress in fixed order calculations during the last (>) decade

  Automation of NLO
  Several NNLO processes $2 \to 2$ ✓
  Even N^{3}LO for simpler kinematics and first set of splitting functions
  QED/EW, BSM effects being automated

  Driven by LHC

- But… Reaching new bottlenecks
- Large multiplicity at NLO still needs *manual*-work
- Loop induced processes (massive) yet hard to tackle
- NNLO very difficult for more than 2 particles in final state
  - Virtual amplitudes (massive)
  - Real radiation not trivial (numerical infrared treatment)

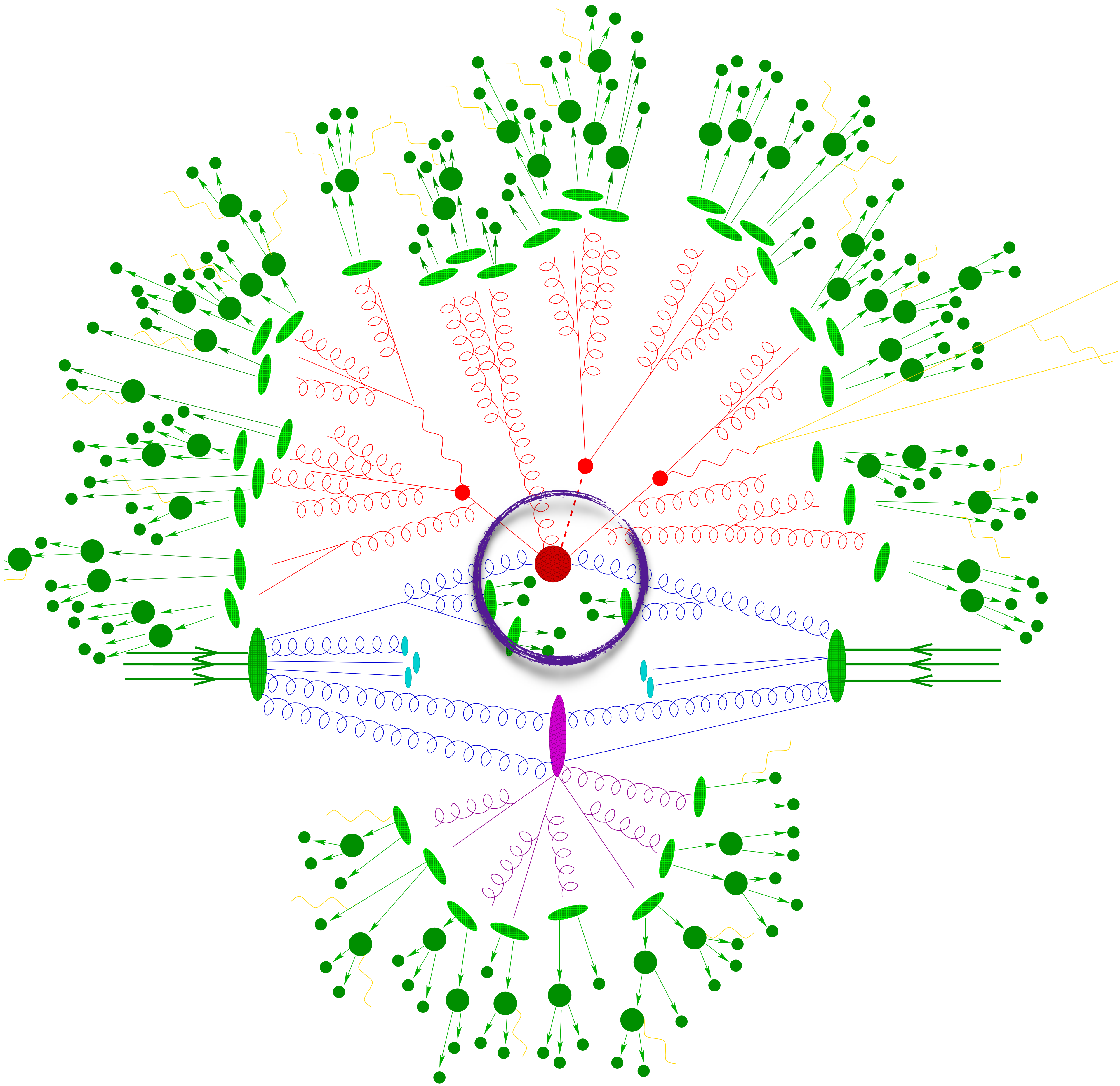
  Will need significant development

- Need a more rigorous treatment of TH uncertainties

High Precision@ Large Hard Calculations

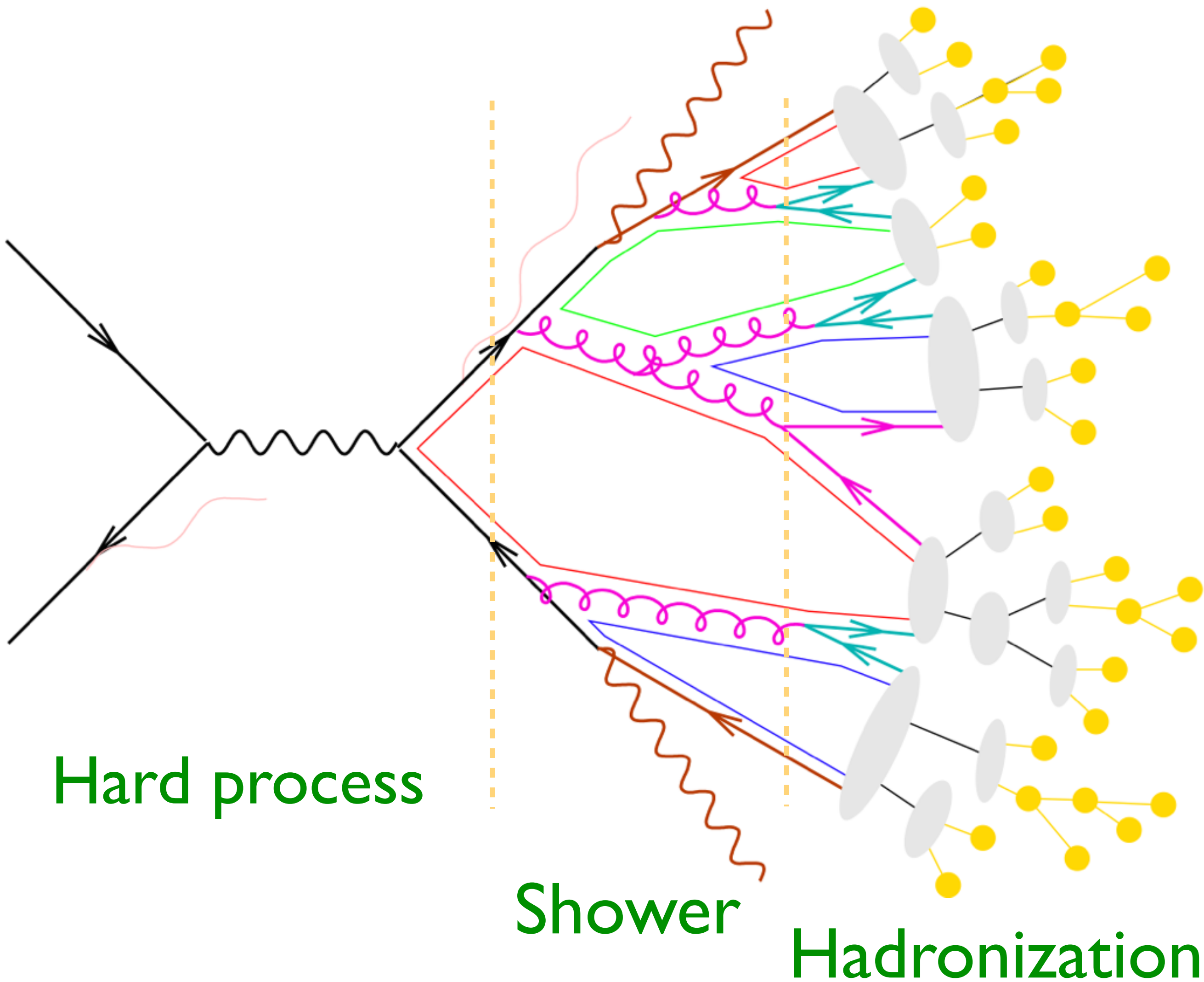
T.Binoth

Backup slides



Fixed order and Parton Showers

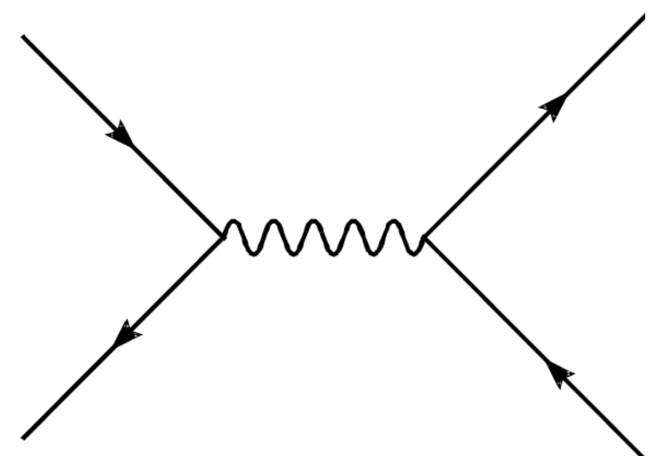
Parton Shower + hadronization



- Resummation to (N)LL accuracy
- Realistic final states
- Based on Born Level

Fixed order

LO



- Fixed order accuracy
- High Precision for inclusive
- Few partons in final state

Fixed order and Parton Showers

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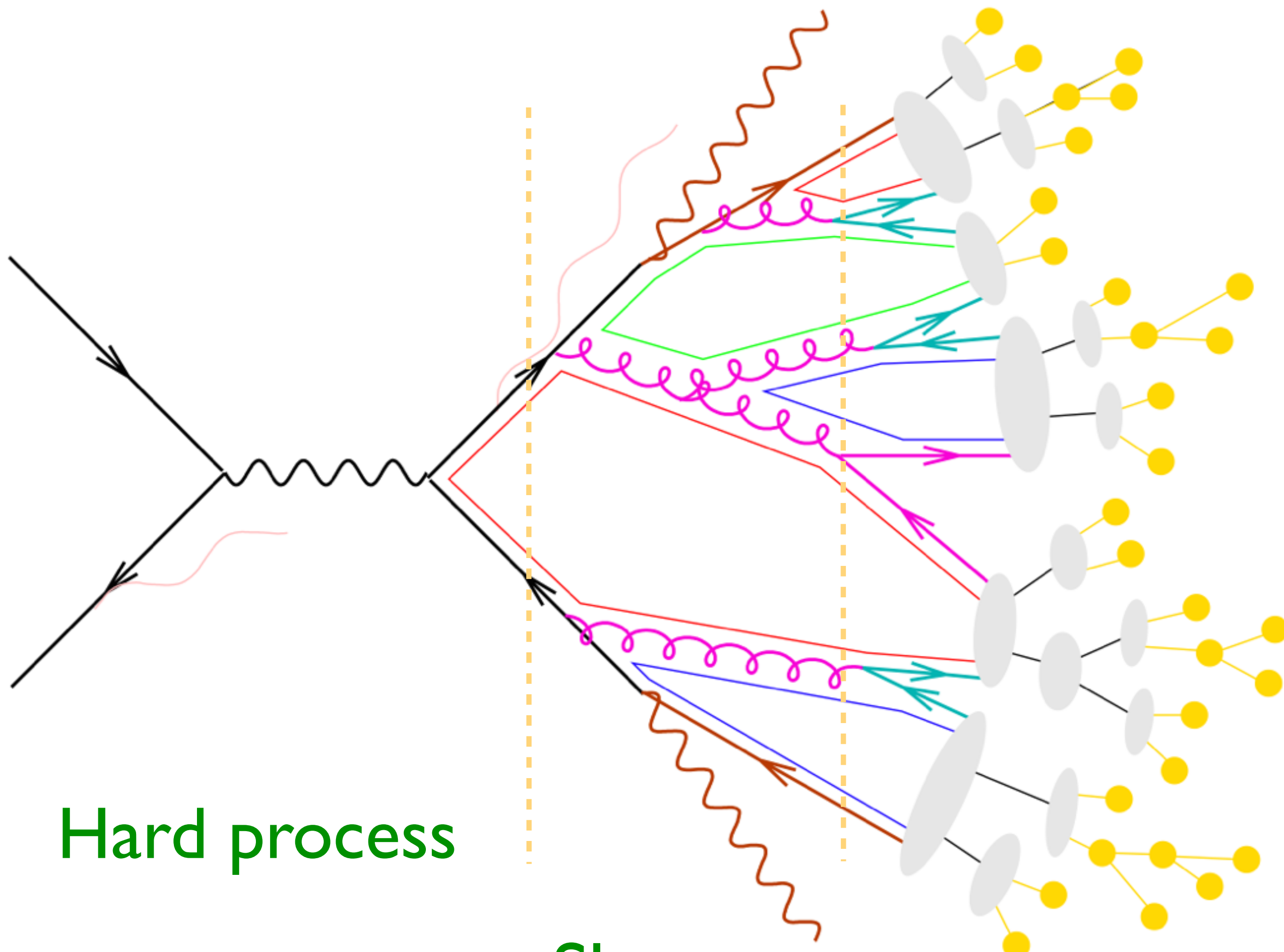

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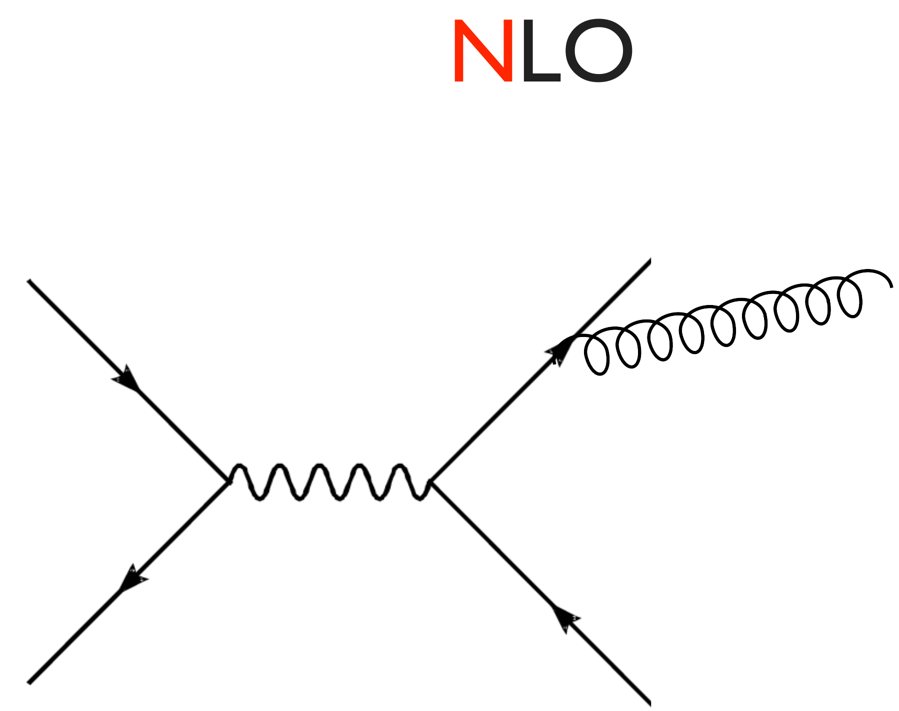

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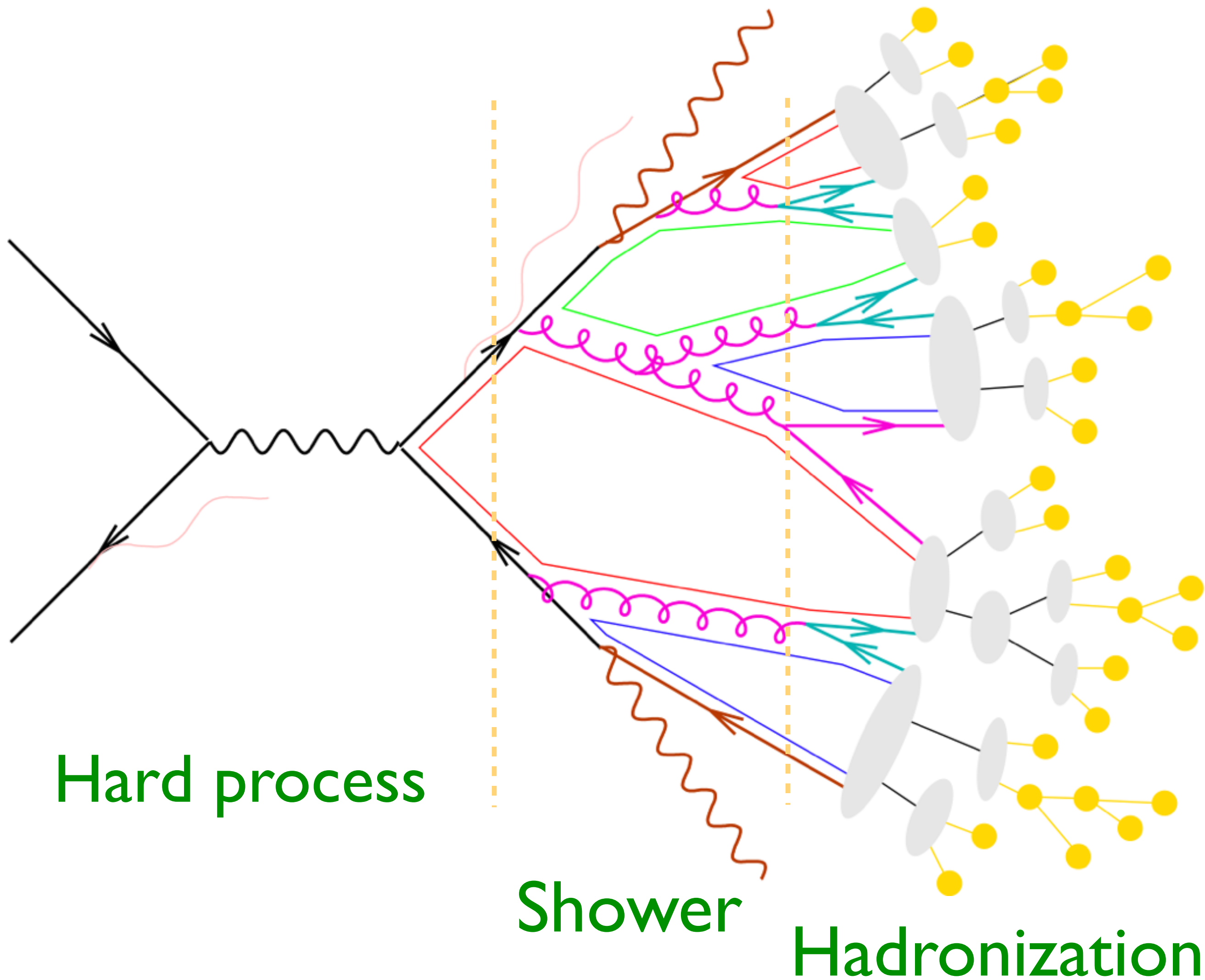

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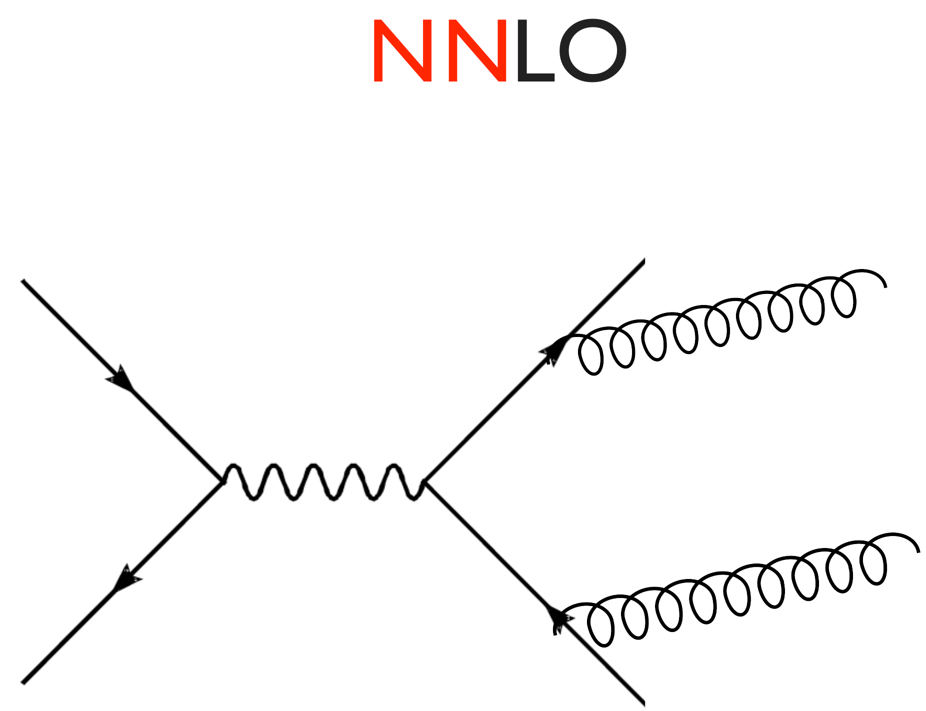

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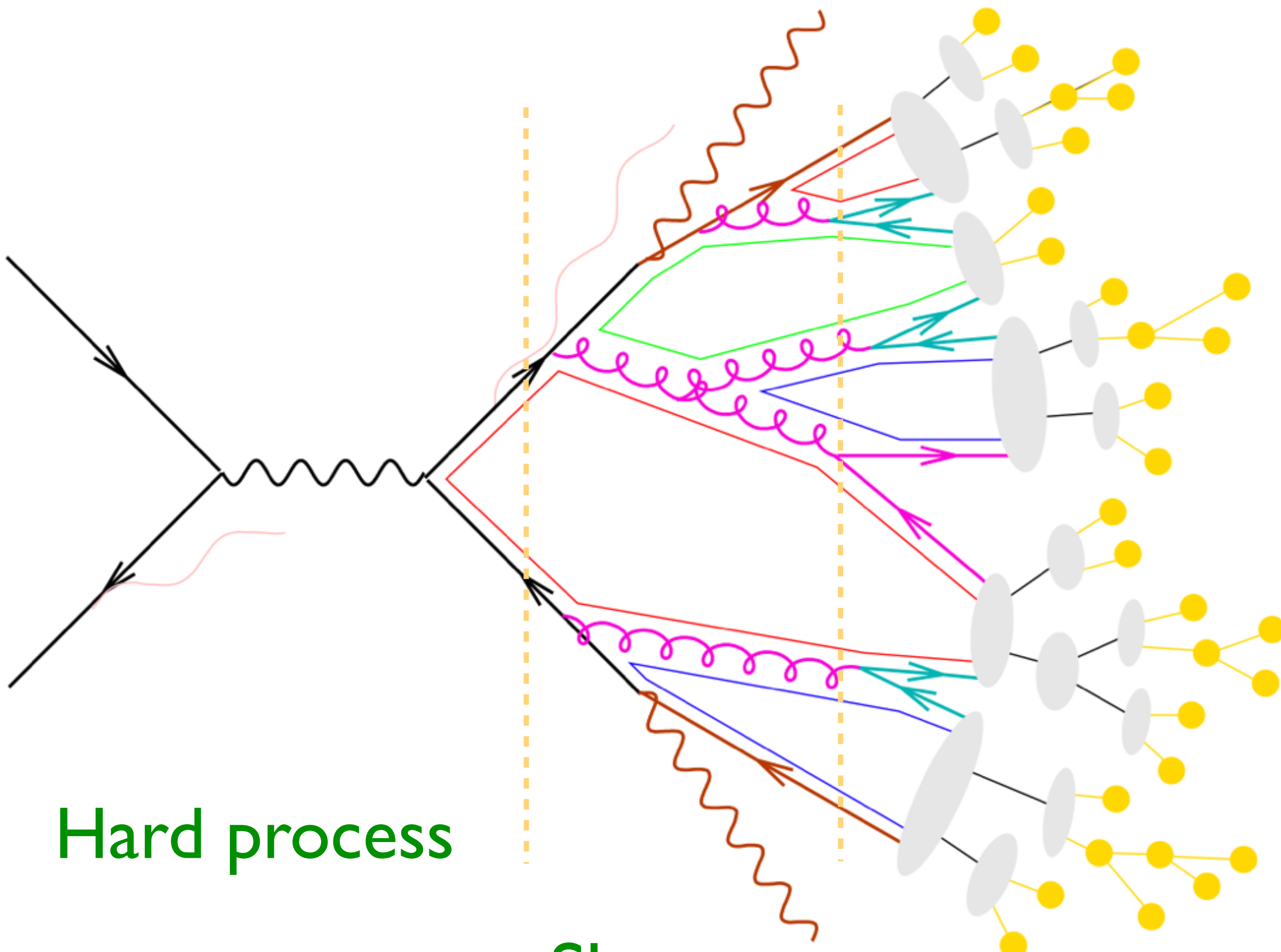

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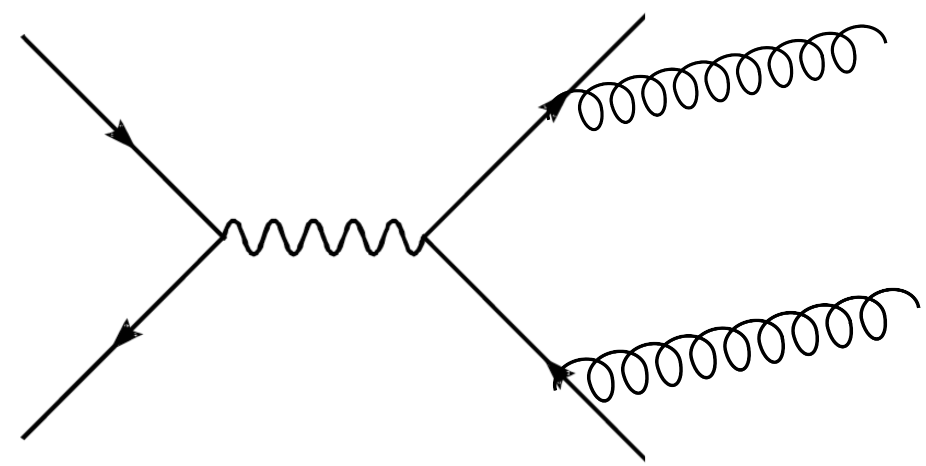
NNLO



- Fixed order accuracy
- High Precision for inclusive
- Few partons in final state

Merging fixed order and parton shower not trivial: double counting

Merging NLO with Parton Showers

- Allow to carry NLO precision to all aspects of experimental analysis

  - MC@NLO Frixione, Webber
  - POWHEG Nason; Frixione, Nason, Oleari

- Can be interfaced to different tools : Herwig, Phytia, Sherpa
- Treat radiation differently but formally same "NL" accuracy

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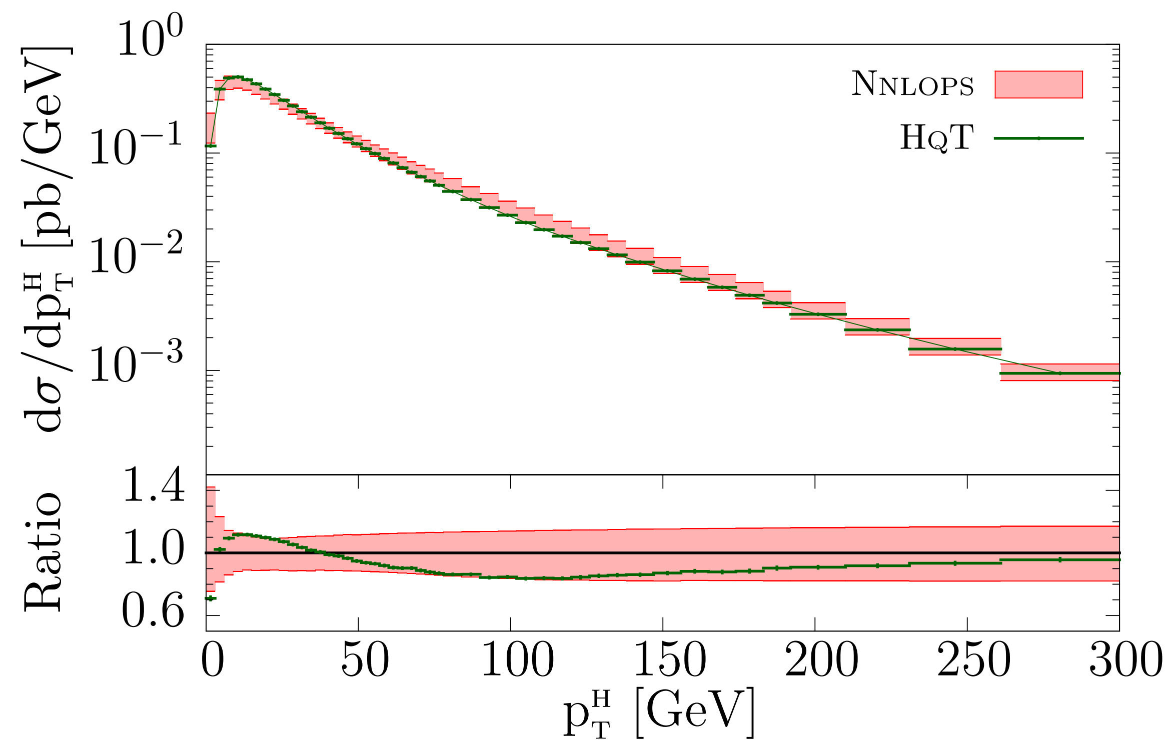
NNLO+PS New

- NNLOPS Hamilton, Nason, Re, Zanderighi

  POWHEG+MINLO

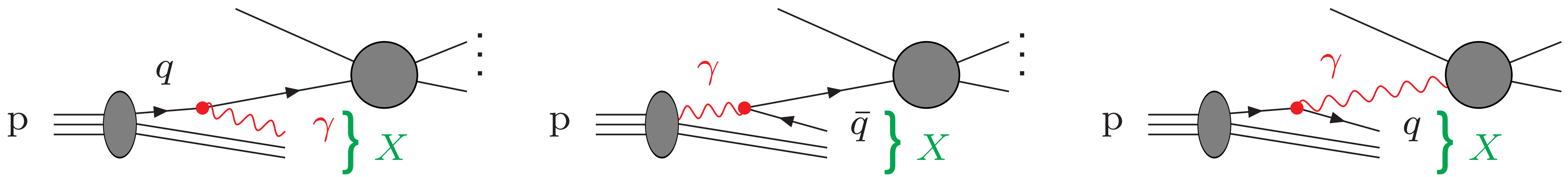
- UN²LOPS, Geneva

  Höche, Li, Prestel



"NNLO" (normalized) but shower still < NLL

New: QED corrections to pdf



- $\mathcal{O}(\alpha)$ corrections to all PDFs

  $\hookrightarrow$ typical impact: $\Delta(\mathrm{PDF}) \lesssim 0.3\%\ (1\%)$ for $x \lesssim 0.1\ (0.4)$, $\mu_{\mathrm{fact}} \sim M_{\mathrm{W}}$

  $\mathcal{O}(\alpha) \sim \mathcal{O}(\alpha_s^2)$ suggests NLO EW $\sim$ NNLO QCD

- by photon emission

  $\hookrightarrow$ kinematical effects, mass-singular log's $\propto \alpha \ln(m_\mu/Q)$ for bare muons, etc.

- at high energies

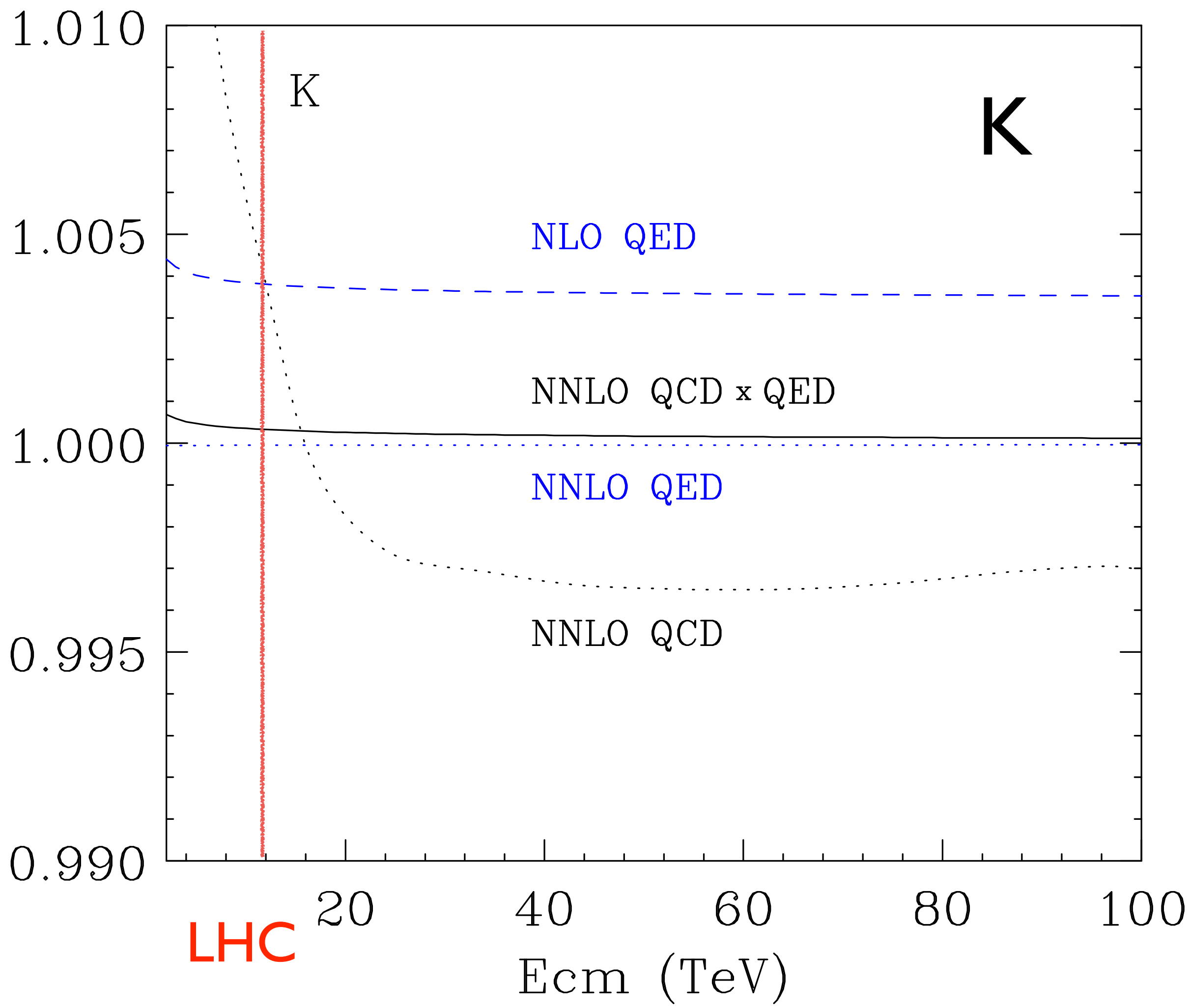
  $\hookrightarrow$ EW Sudakov log's $\propto (\alpha/s_{\mathrm{W}}^2)\ln^2(M_{\mathrm{W}}/Q)$ and subleading log's

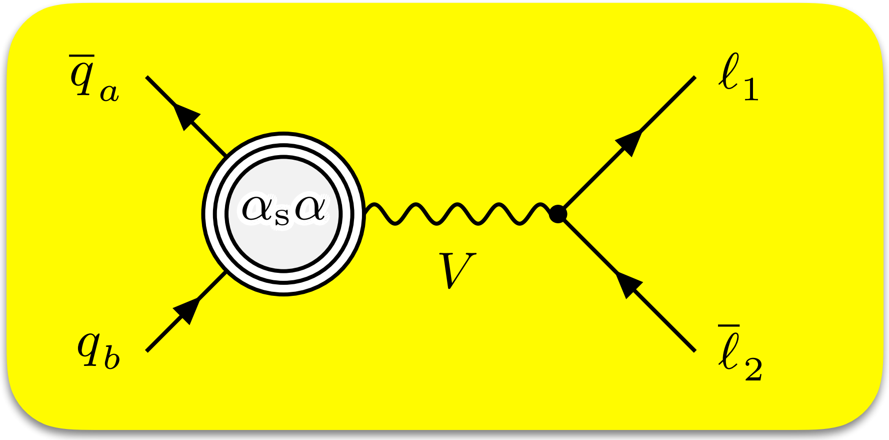
LUXqed :precise determination of photon content of the proton Manohar et al (2016)

QED-QCD splitting functions DdeF, Rodrigo, Sborlini (2016)

NNLO QED+QCD for Drell-Yan

$\alpha_s^2 \quad \alpha_s\alpha \quad \alpha^2$





$$K_{QED}^{NLO} = \frac{\sigma^{(0,0)} + \alpha\,\sigma^{(0,1)}}{\sigma^{(0,0)}}$$

$$K_{QCD}^{NNLO} = \frac{\sigma^{(0,0)} + \alpha_s\,\sigma^{(1,0)} + \alpha_s^2\,\sigma^{(2,0)}}{\sigma^{(0,0)} + \alpha_s\,\sigma^{(1,0)}}$$

$$K_{QED}^{NNLO} = \frac{\sigma^{(0,0)} + \alpha\,\sigma^{(0,1)} + \alpha^2\,\sigma^{(0,2)}}{\sigma^{(0,0)} + \alpha\,\sigma^{(0,1)}}$$

$$K_{QCD\times QED}^{NNLO} = \frac{\sigma^{(0,0)} + \alpha\,\sigma^{(0,1)} + \alpha_s\,\sigma^{(1,0)} + \alpha\alpha_s\,\sigma^{(1,1)}}{\sigma^{(0,0)} + \alpha\,\sigma^{(0,1)} + \alpha_s\,\sigma^{(1,0)}}$$

- $\alpha_s^2 \sim \alpha$ QED NLO ~ QCD NNLO around 5 per-mille
- Mixed QEDxQCD below the per-mille level (max. ~ 2 TeV)
- At 14 TeV QCD NNLO ~ 3.5 mixed QEDxQCD (not ~15)
- $\mathrm{QED}^2 \sim \mathcal{O}(10^{-5})$ DdeF, M. Der, I. Fabre

TH Uncertainties

$$\sigma = 48.58\,\text{pb}^{+2.22\,\text{pb}\,(+4.56\%)}_{-3.27\,\text{pb}\,(-6.72\%)}\ (\text{theory}) \pm 1.56\,\text{pb}\,(3.20\%)\ (\text{PDF+}\alpha_s)$$

what is the meaning of that?

- Usually obtained by performing scale variations

$$\log\frac{Q}{\mu} \qquad \log\frac{\mu_F}{\mu_R} \qquad \log\frac{Q}{\mu_{F,R}}$$

keep logs small

$$\mu_{F,R} = \left(r, \frac{1}{r}\right) Q$$

- Lack of probabilistic framework : how to combine with other?
- Several examples showing that "*r*=2" might be short to account for true uncertainties

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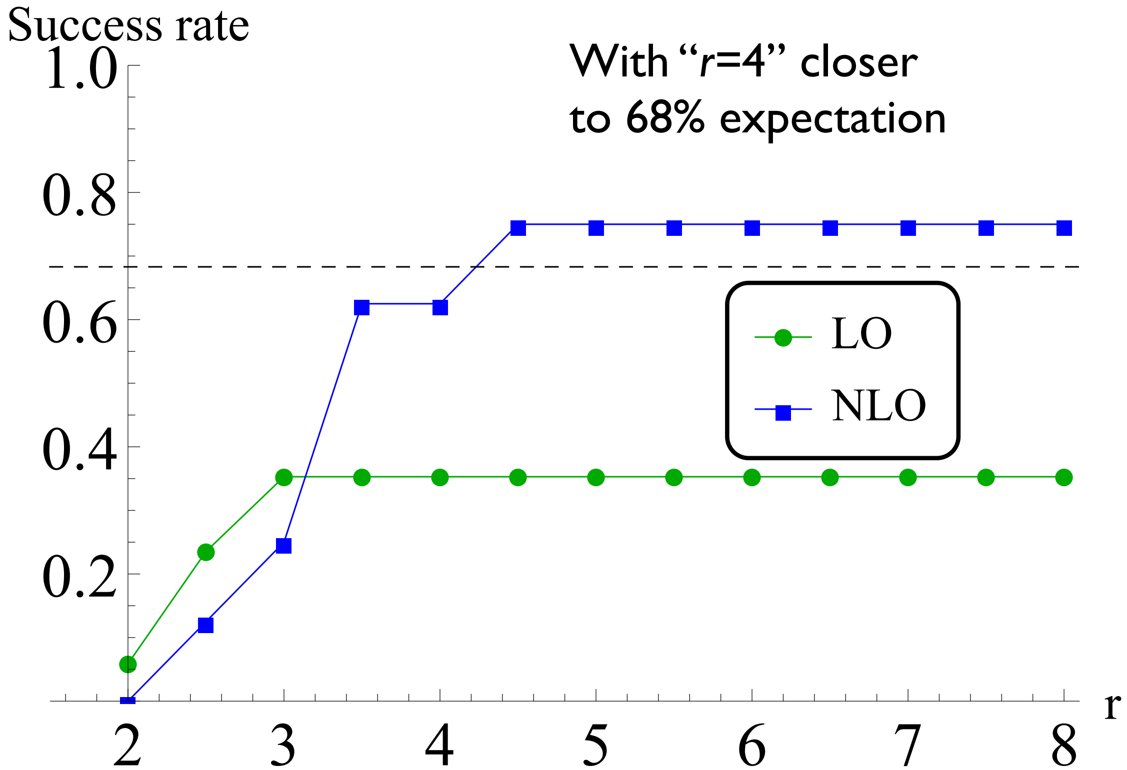
- Several examples showing that "*r*=2" might be short to account for true uncertainties

  - Fraction of hadronic observables (~15) whose h.o. correction is contained in the scale variation interval

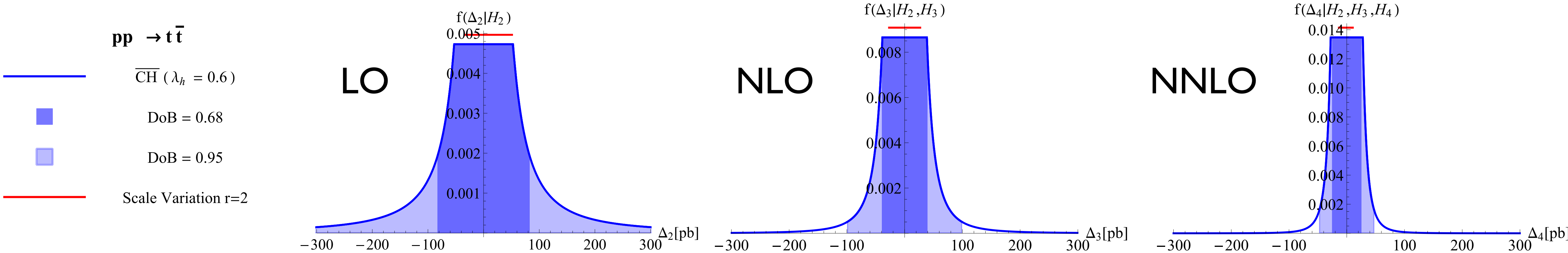
    E. Bagnaschi, M. Cacciari, A. Guffanti, L. Jenniches (2014)

  - But *rescaling* depends on order: might be better from NNLO



Bayesian approach: Introduce condicional density compute credibility interval with degree of belief (68%, 95%)

M. Cacciari, N. Houdeau (2011); E. Bagnaschi, M. Cacciari, A. Guffanti, L. Jenniches (2014)



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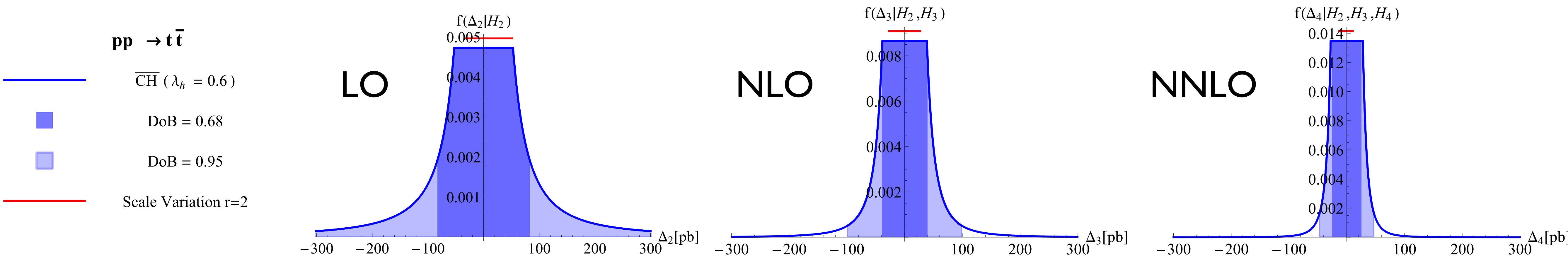

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- Series acceleration: estimate some unknown terms using analytical structure of expansion and sequence methods A. David, G. Passarino (2013)

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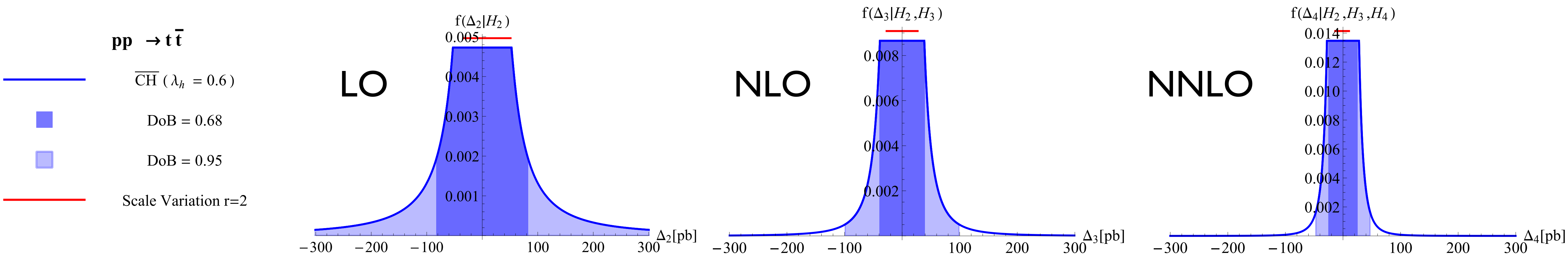

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Too much effort to reach N^nLO to avoid the search for a more rigorous handling of TH uncertainties in perturbative calculations

Resummation

- QCD based on convergence of perturbative expansion

$$\sigma = \mathcal{C}_0 + \alpha_s \mathcal{C}_1 + \alpha_s^2 \mathcal{C}_2 + \alpha_s^3 \mathcal{C}_3 + \ldots$$

requires $\alpha_s \ll 1 \ , \ \mathcal{C}_n \sim \mathcal{O}(1)$

In the boundaries of phase space → soft and collinear emission

unbalance cancellation of infrared singularities
between real and virtual contributions

- Convergence spoiled when two scales are very different

$L = |\log \frac{E_1}{E_2}| \gg 1$ $\quad\quad$ $\mathcal{C}_m \sim L^n \quad n \sim 2m$

low transverse momentum	$\log \frac{q_T}{Q}$	DY, Higgs
threshold	$\log \left(1 - \frac{Q^2}{\hat{s}}\right)$	Higgs, HQ
high energy	$\log x$	DIS BFKL

$\alpha_s L \simeq 1$ $\quad \alpha_s \sim 0.1 \quad L \sim 1/\alpha_s \sim 10$

- Reorganization of expansion $(\alpha_S L)^n$

Fixed order →

Resummation ↓

	LL	NLL	NNLL		
LO	1				
NLO	$\alpha_s L^2$	$\alpha_s L$	α_s	$+ \dots$	↓ α_s
NNLO	$\alpha_s^2 L^4$	$\alpha_s^2 L^3$	$\alpha_s^2 L^2$	$\alpha_s^2 L \quad + \dots$	↓ α_s
	$\alpha_s^3 L^6$	$\alpha_s^3 L^5$	$\alpha_s^3 L^4$	$\alpha_s^3 L^3 \quad + \dots$	
	$\alpha_s^4 L^8$	$\alpha_s^4 L^7$	$\alpha_s^4 L^6$	$\alpha_s^4 L^5 \quad + \dots$	
	$\vdots$	$\vdots$	$\vdots$	$\vdots$	
N^{k}LO	$\alpha_s^k L^{2k}$	$\alpha_s^k L^{2k-1}$	$\alpha_s^k L^{2k-2}$	$\alpha_s^k L^{2k-3} \quad + \dots$	

LL $\;1/L\;$ **NLL** $\;1/L\;$ **NNLL**