Precision QCD at the LHC

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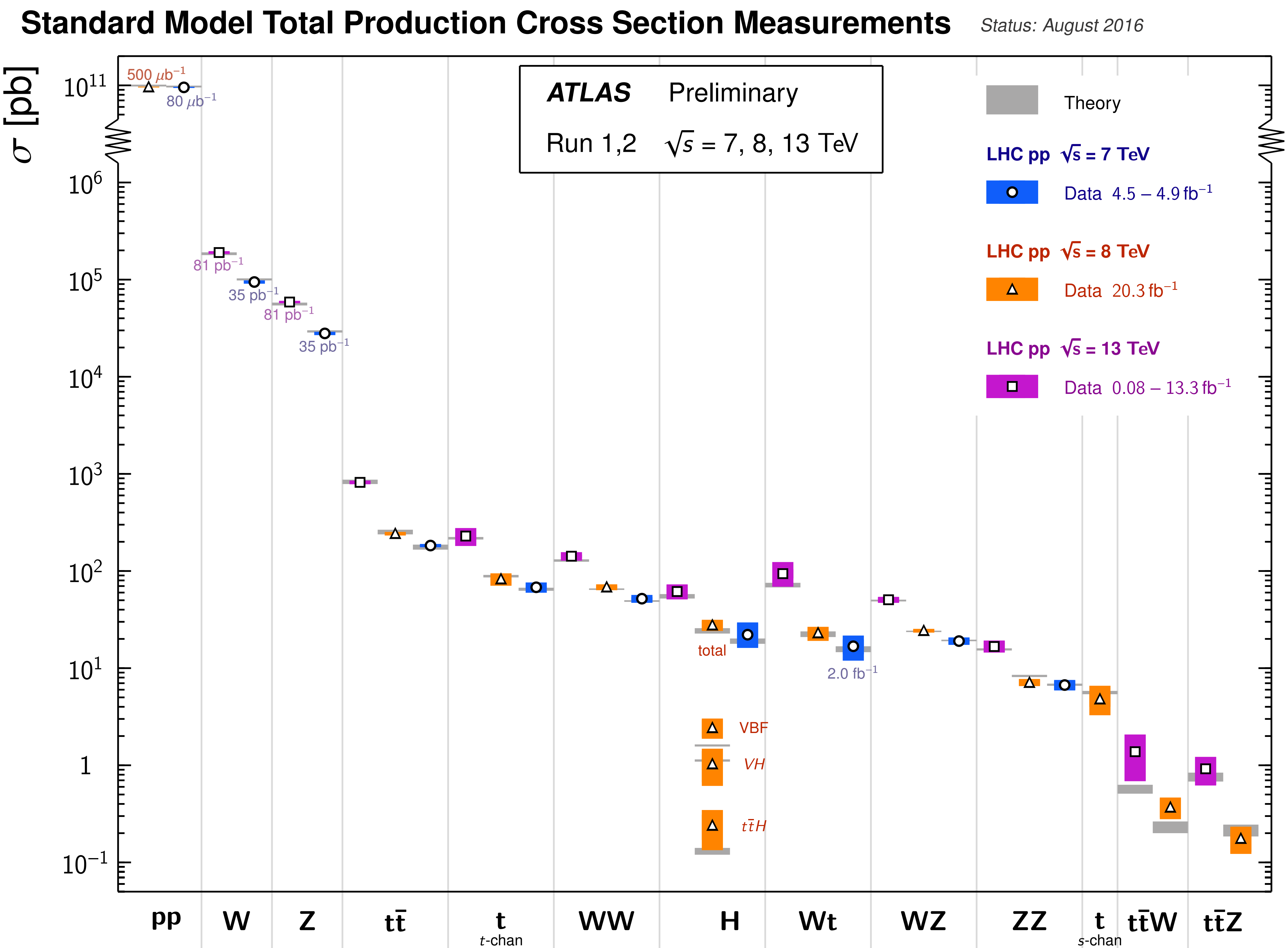
Workshop on Determination of Fundamental QCD Parameters

October 4, 2019
ICTP-SAIFR São Paulo

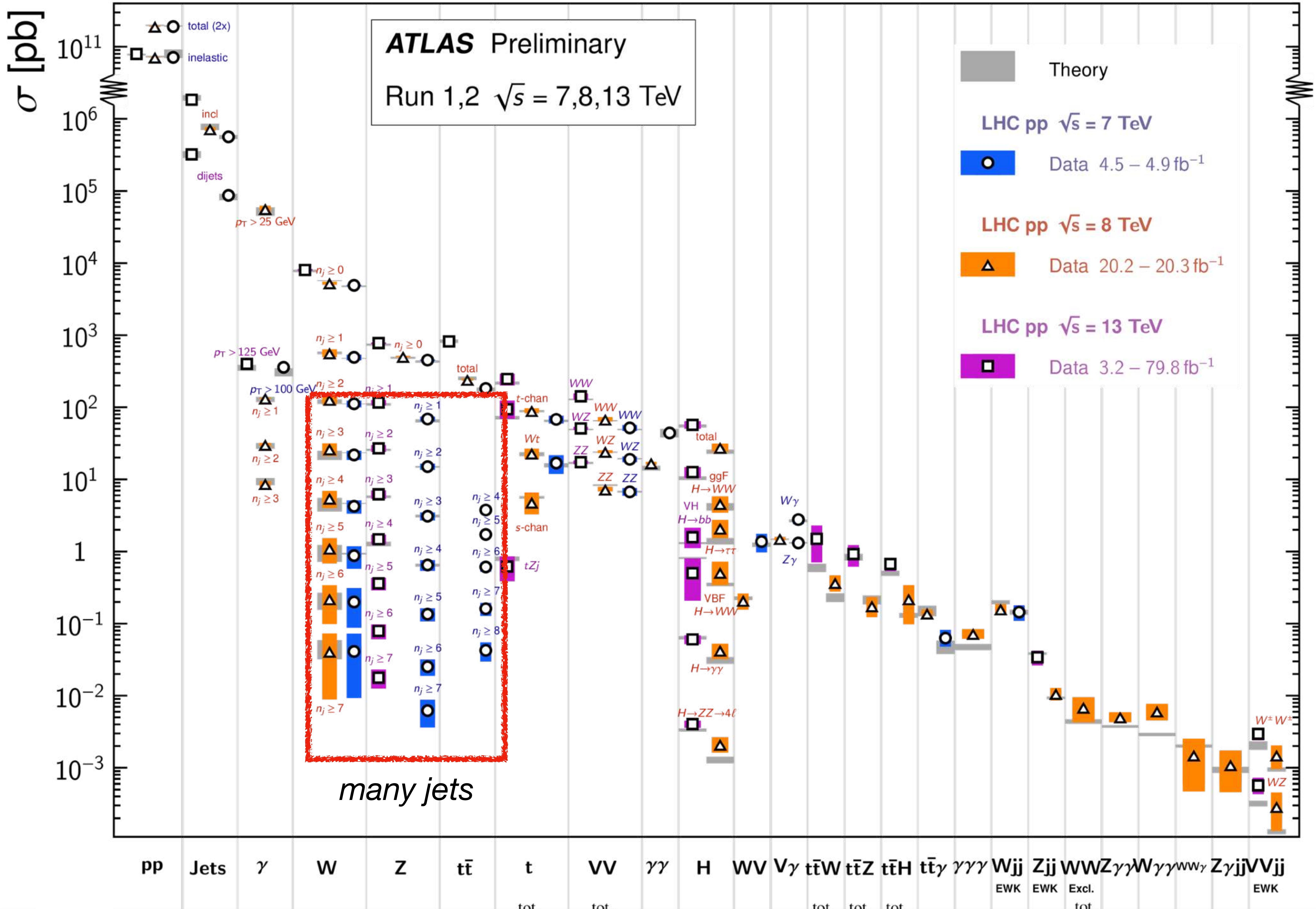
- LHC incredibly successful at 7 , 8 & 13 TeV (Runs I and II)



- Everything SM like (including Higgs)

Standard Model Production Cross Section Measurements

Status: July 2018



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

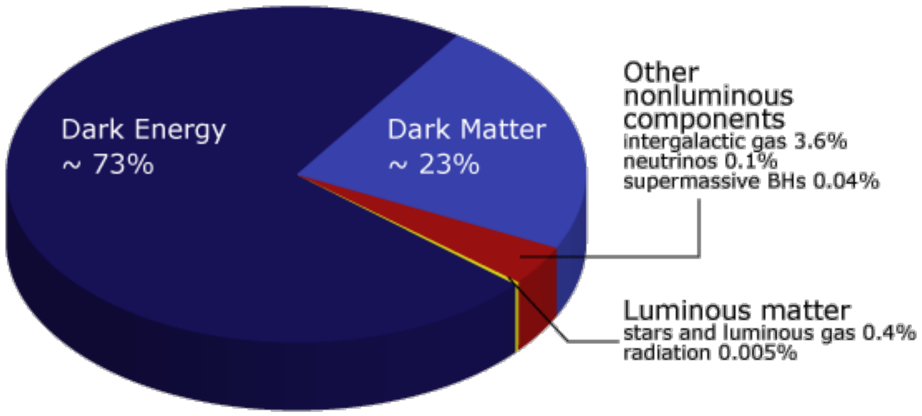
- Lacks description of Quantum Gravity
- Hierarchy, naturalness problems

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

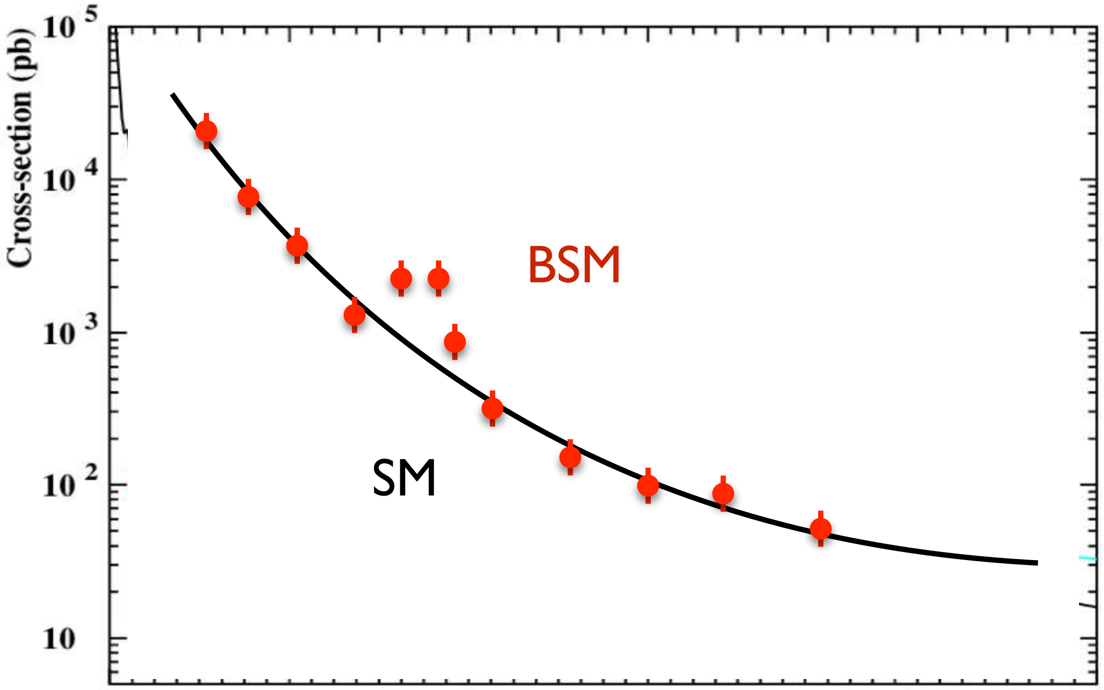
13 orders of magnitude between lightest and heaviest particle

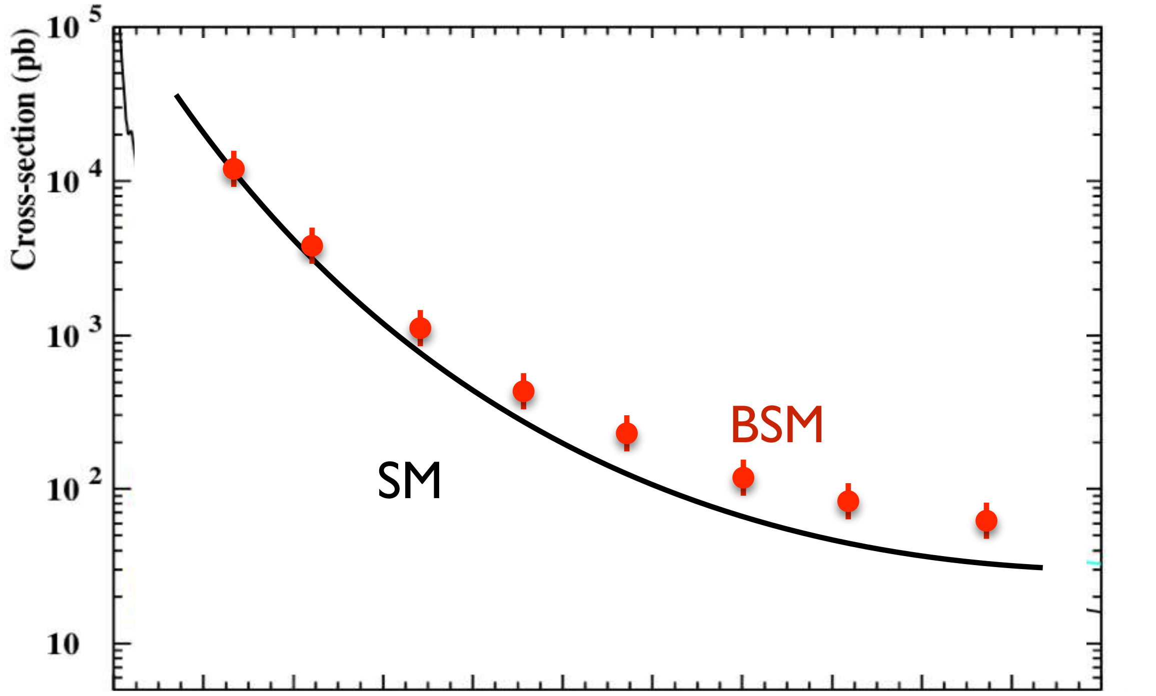
Finer tuning in Higgs sector

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

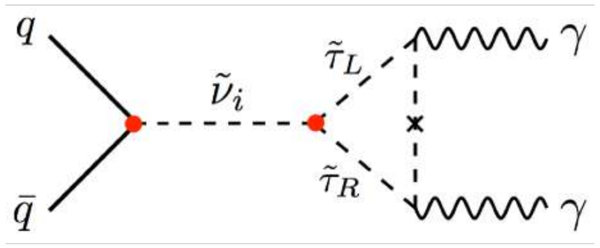


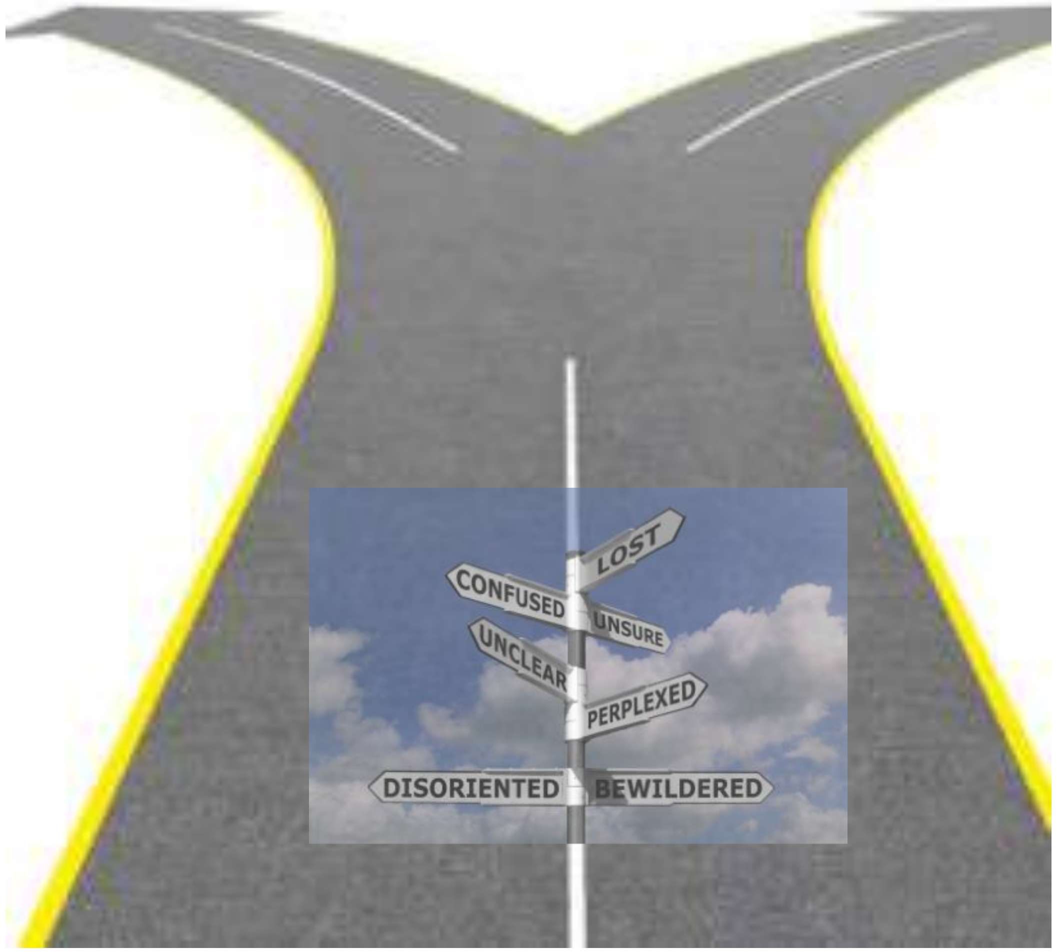
There are(?) TH candidates, but search is DRIVEN BY EXPERIMENTS now



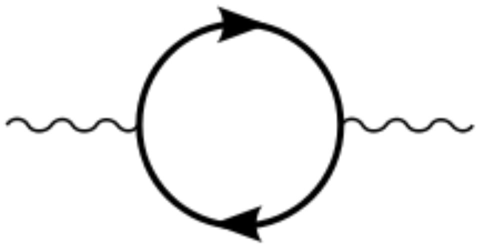


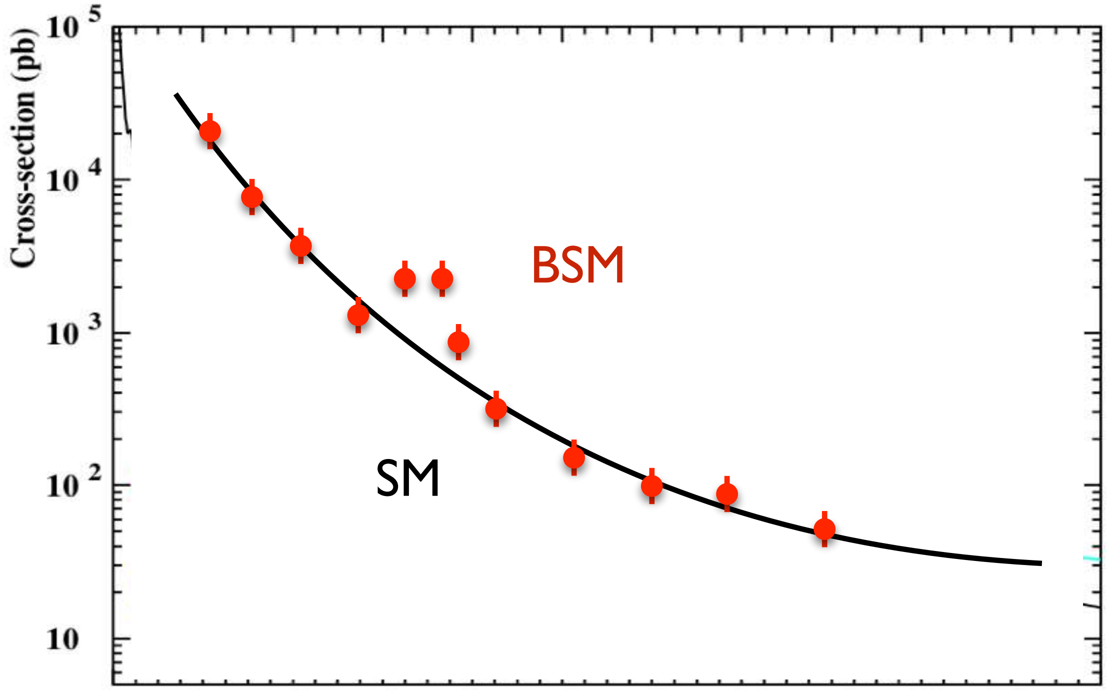
Search for new *states*
Resonances
"Descriptive TH"

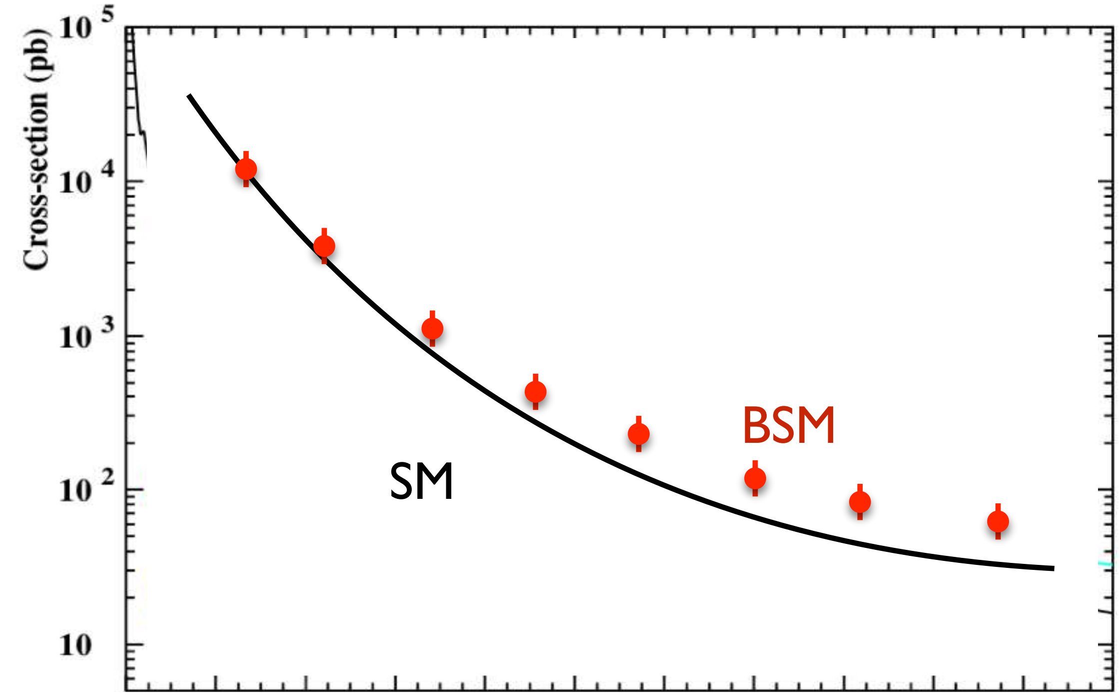




Search for new *interactions*
Deviations from TH
"Precision TH"







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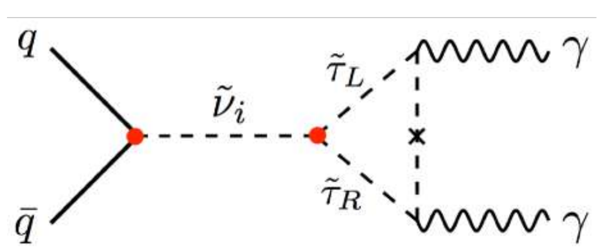

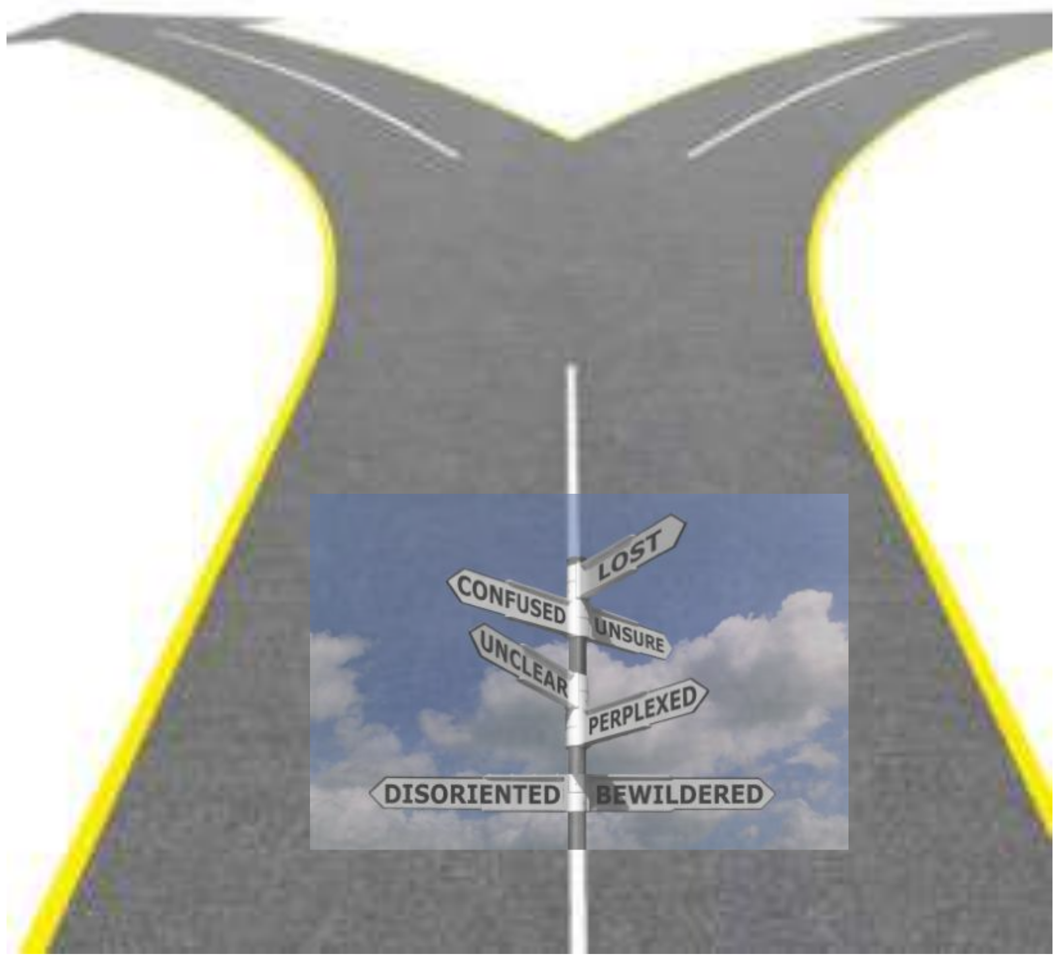

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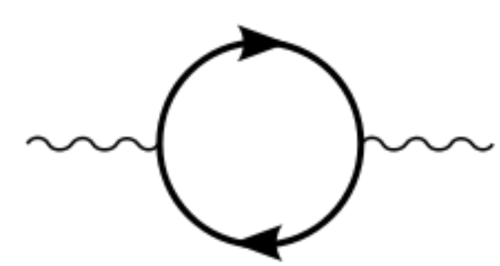
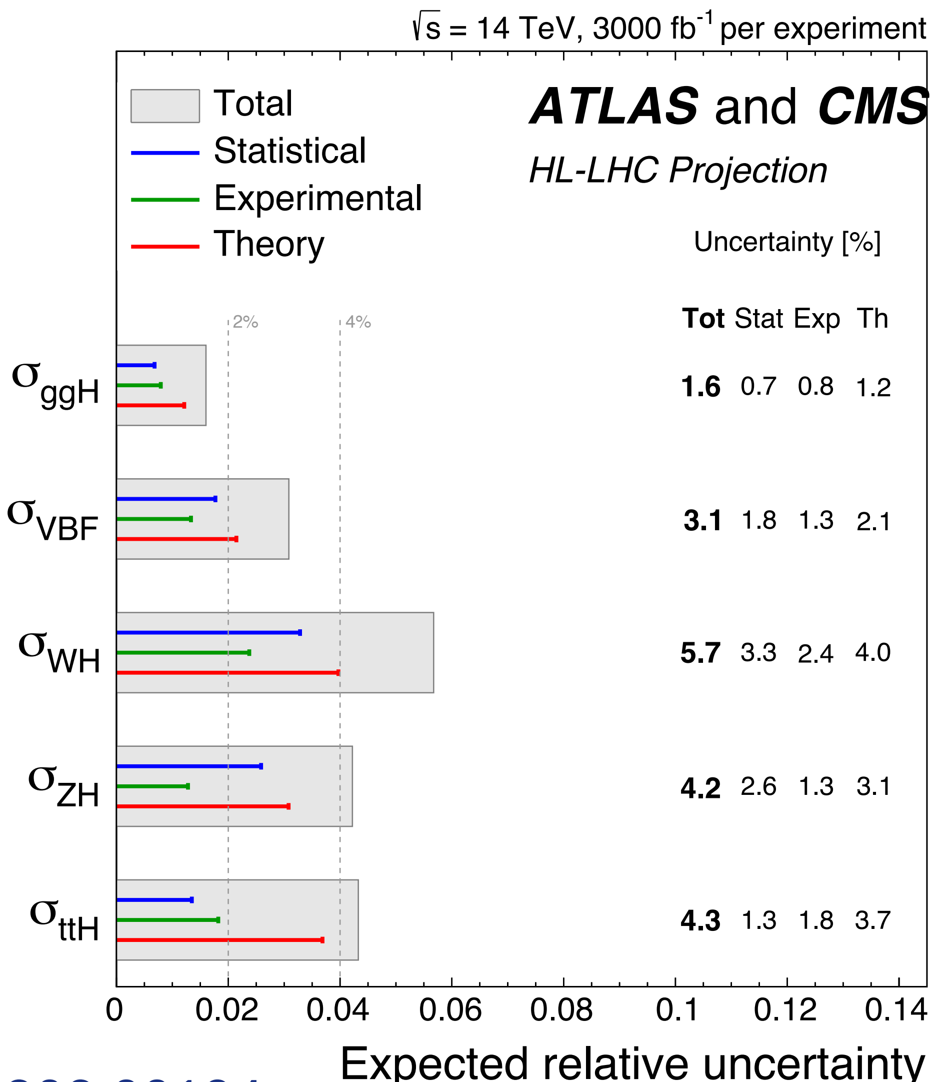


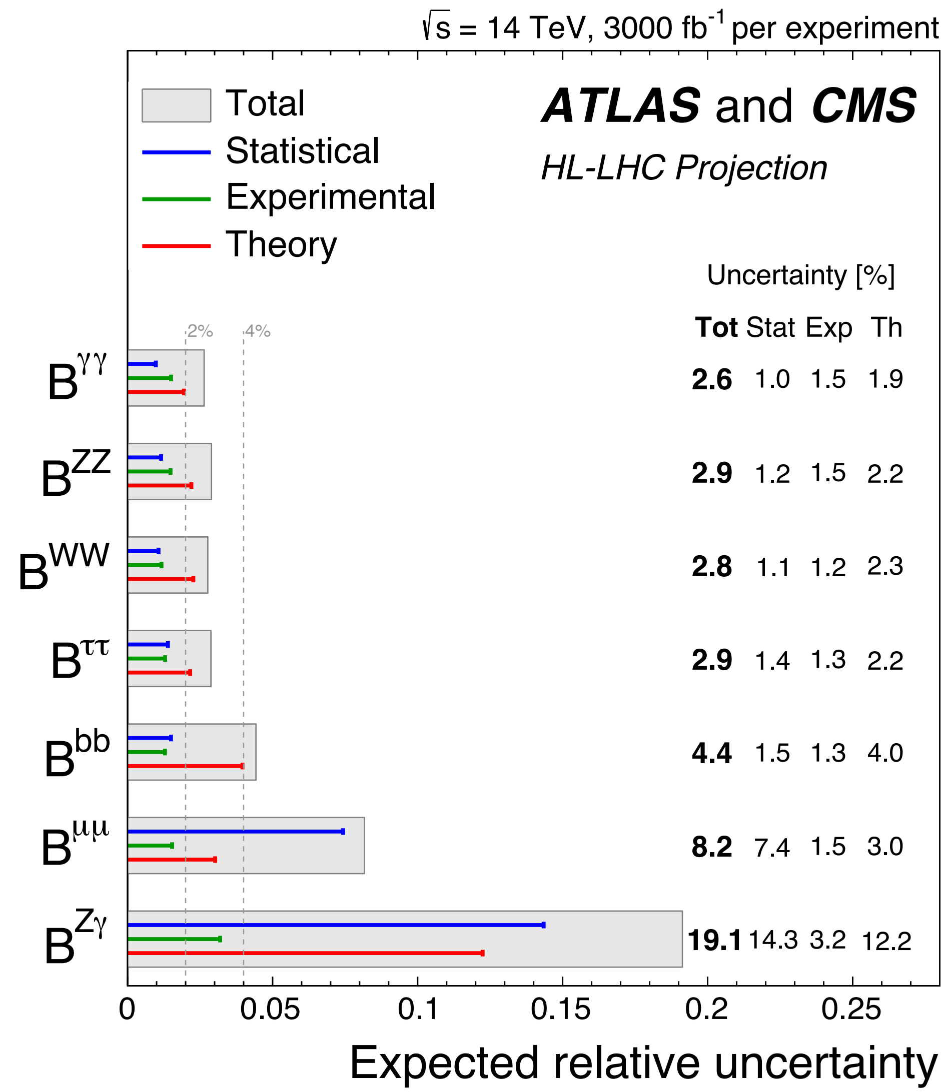
- Need for precision ~ 1% EXP-TH accuracy (HIGGS very relevant)

HL-LHC projections

~20 years from now!

(S2) TH uncertainties scaled down by factor 2, EXP scaled according to $\sqrt{\mathscr{L}}$





1902.00134

TH errors may dominate

- Precision becomes critical
- TH: can we improve calculations? are we missing sources of uncertainty?
- EXP: using the most accurate results?

- 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

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

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	$\varepsilon^{IJK}W_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$	$Q_{\varphi D}$	$\left(\varphi^\dagger D^\mu\varphi\right)^\star\left(\varphi^\dagger D_\mu\varphi\right)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar{q}_p d_r \varphi)$
$Q_{\widetilde{W}}$	$\varepsilon^{IJK}\widetilde{W}_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$				
$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G_{\mu\nu}^A G^{A\mu\nu}$	Q_{eW}	$(\bar{l}_p\sigma^{\mu\nu}e_r)\tau^I\varphi W_{\mu\nu}^I$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{l}_p\gamma^\mu l_r)$
$Q_{\varphi\widetilde{G}}$	$\varphi^\dagger\varphi\, \widetilde{G}_{\mu\nu}^A G^{A\mu\nu}$	Q_{eB}	$(\bar{l}_p\sigma^{\mu\nu}e_r)\varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu^I\varphi)(\bar{l}_p\tau^I\gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W_{\mu\nu}^I W^{I\mu\nu}$	Q_{uG}	$(\bar{q}_p\sigma^{\mu\nu}T^A u_r)\widetilde{\varphi}\, G_{\mu\nu}^A$	$Q_{\varphi e}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{e}_p\gamma^\mu e_r)$
$Q_{\varphi\widetilde{W}}$	$\varphi^\dagger\varphi\, \widetilde{W}_{\mu\nu}^I W^{I\mu\nu}$	Q_{uW}	$(\bar{q}_p\sigma^{\mu\nu}u_r)\tau^I\widetilde{\varphi}\, W_{\mu\nu}^I$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{q}_p\gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu}B^{\mu\nu}$	Q_{uB}	$(\bar{q}_p\sigma^{\mu\nu}u_r)\widetilde{\varphi}\, B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu^I\varphi)(\bar{q}_p\tau^I\gamma^\mu q_r)$
$Q_{\varphi\widetilde{B}}$	$\varphi^\dagger\varphi\, \widetilde{B}_{\mu\nu}B^{\mu\nu}$	Q_{dG}	$(\bar{q}_p\sigma^{\mu\nu}T^A d_r)\varphi\, G_{\mu\nu}^A$	$Q_{\varphi u}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{u}_p\gamma^\mu u_r)$
$Q_{\varphi WB}$	$\varphi^\dagger\tau^I\varphi\, W_{\mu\nu}^I B^{\mu\nu}$	Q_{dW}	$(\bar{q}_p\sigma^{\mu\nu}d_r)\tau^I\varphi\, W_{\mu\nu}^I$	$Q_{\varphi d}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{d}_p\gamma^\mu d_r)$
$Q_{\varphi\widetilde{W}B}$	$\varphi^\dagger\tau^I\varphi\, \widetilde{W}_{\mu\nu}^I B^{\mu\nu}$	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

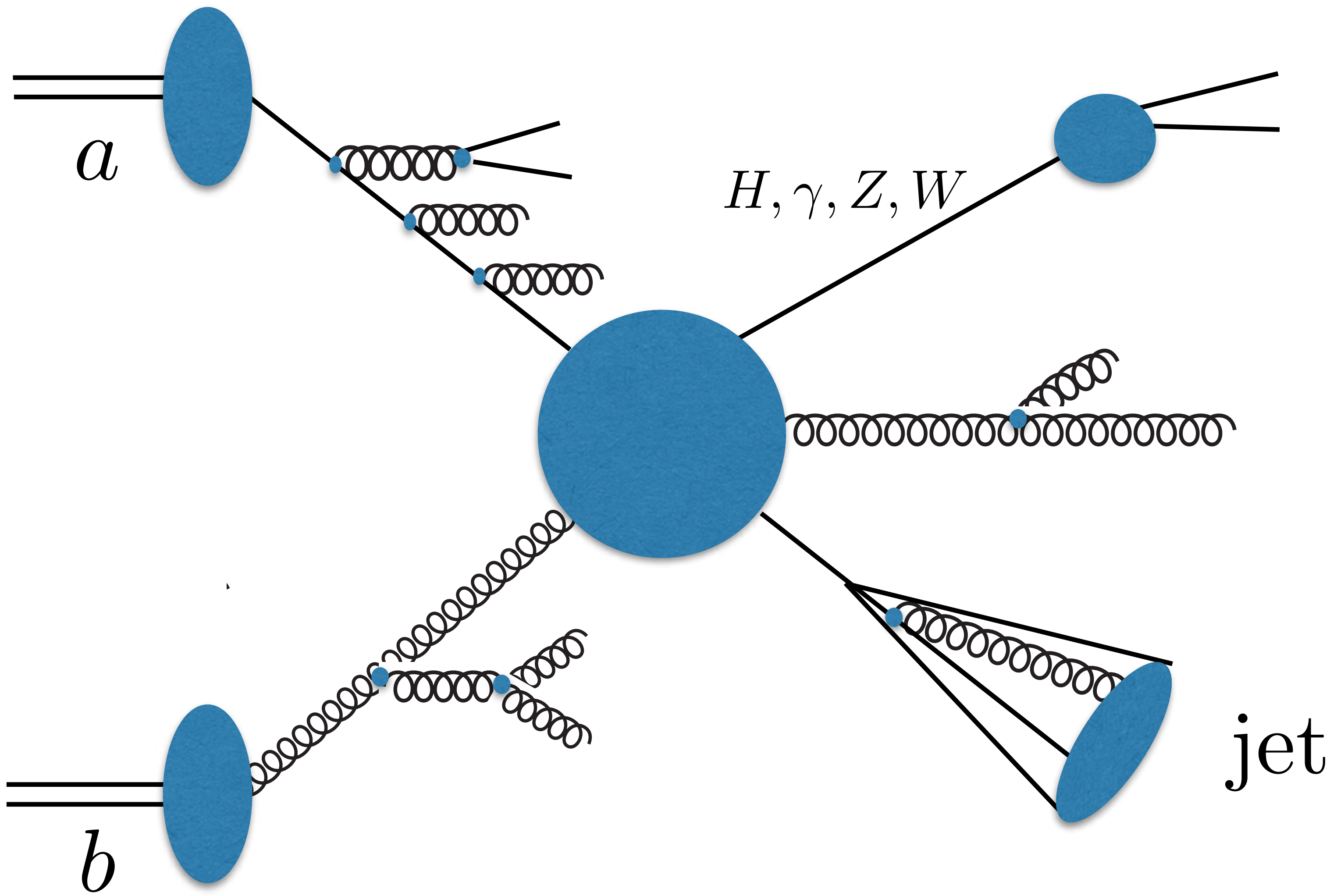
Outline

pQCD @ LHC

precision perturbative production

- PDFs
- NLO
- NNLO and even N^3LO
- 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

fundamental QCD parameters

$$d\sigma = \sum_{ab} \int dx_a \int dx_b \, f_a(x_a, \mu_F^2) f_b(x_b, \mu_F^2) \times d\hat{\sigma}_{ab}(x_a, x_b, Q^2, \alpha_s(\mu_R^2))$$

LO

Born level partonic cross section

pdfs obtained from a LO analysis and 1 loop AP

$\alpha_s(m_q)$ obtained from a LO analysis and evolved with 1 loop β

NLO

1-loop level partonic cross section

pdfs obtained from a NLO analysis and 2 loop AP

$\alpha_s(m_q)$ obtained from a NLO analysis and evolved with 2 loop β

NNLO

2-loop level partonic cross section

pdfs obtained from a NNLO analysis and 3 loop AP

$\alpha_s(m_q)$ obtained from a NNLO analysis and evolved with 3 loop β

$$d\sigma = \sum_{ab} \int dx_a \int dx_b \, f_a(x_a, \mu_F^2) f_b(x_b, \mu_F^2) \times d\hat{\sigma}_{ab}(x_a, x_b, Q^2, \alpha_s(\mu_R^2))$$

LO

$\alpha_s^{\mathrm{LO}}(m_Z) \sim 0.13$

Born level partonic cross section

pdfs obtained from a LO analysis and 1 loop AP

$\alpha_s(m_q)$ obtained from a LO analysis and evolved with 1 loop β

NLO

1-loop level partonic cross section $\alpha_s^{\mathrm{NLO}}(m_Z) = 0.12067 \pm 0.00064$

pdfs obtained from a NLO analysis and 2 loop AP

$\alpha_s(m_q)$ obtained from a NLO analysis and evolved with 2 loop β

NNLO

2-loop level partonic cross section $\alpha_s^{\mathrm{NNLO}}(m_Z) = 0.11845 \pm 0.00052$

pdfs obtained from a NNLO analysis and 3 loop AP

$\alpha_s(m_q)$ obtained from a NNLO analysis and evolved with 3 loop β

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')

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15% for H!!

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PDFs

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HQ masses

15% for H!!

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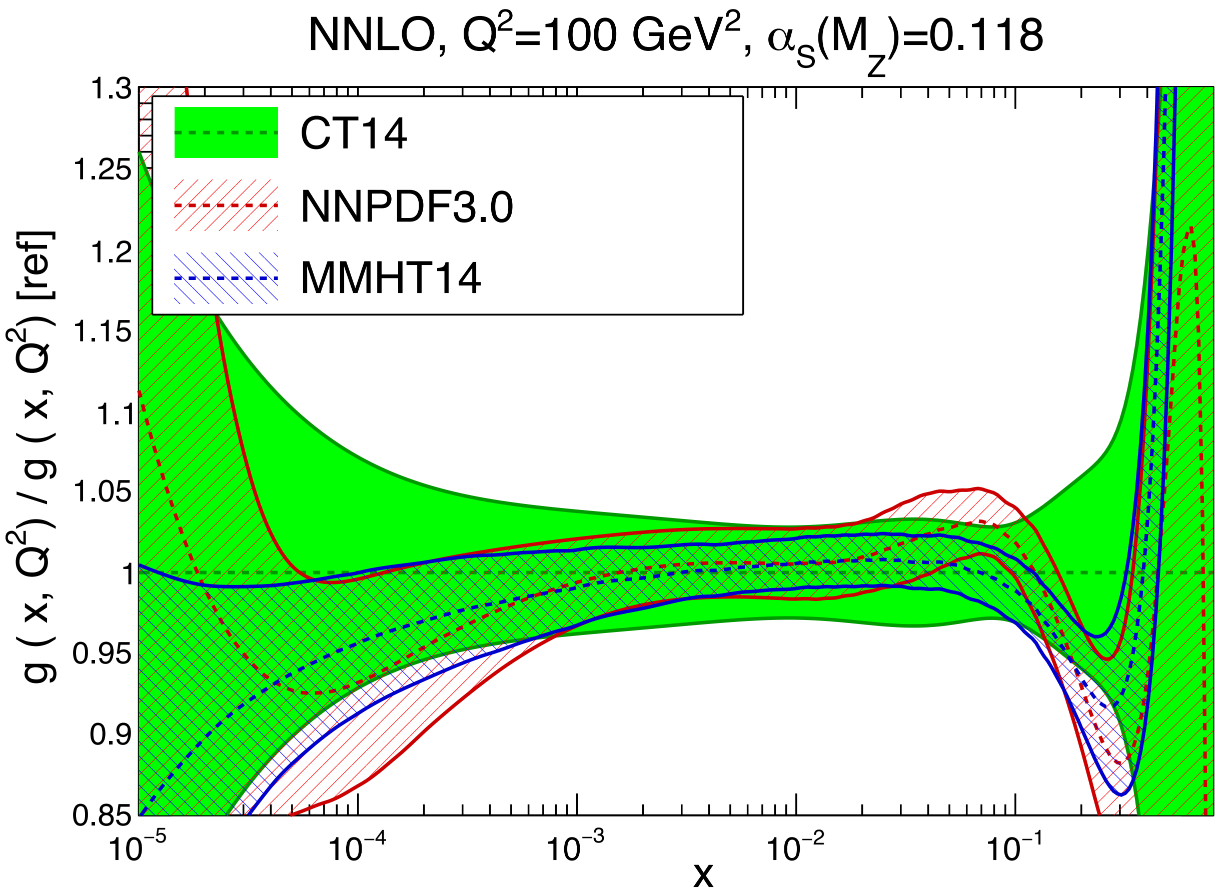
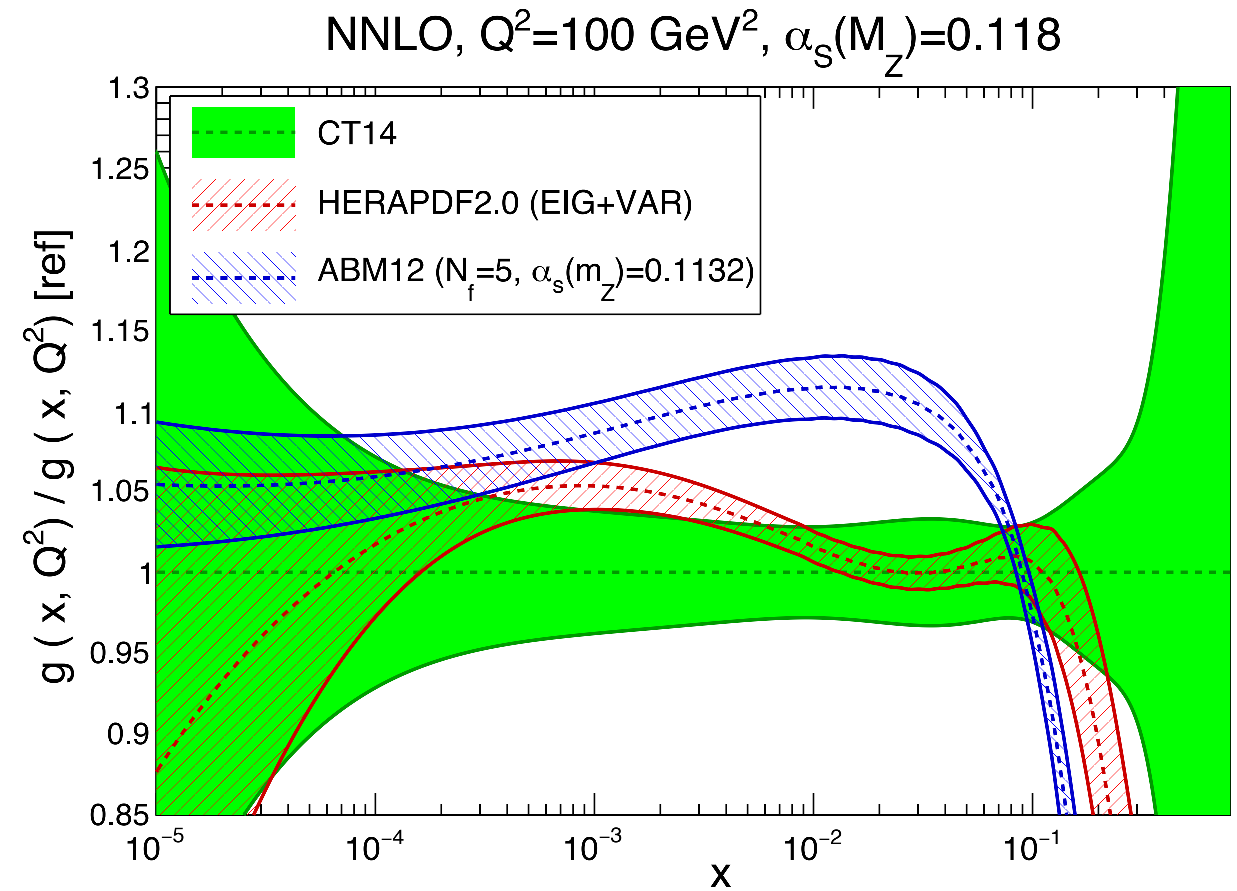
PDF4LHC

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





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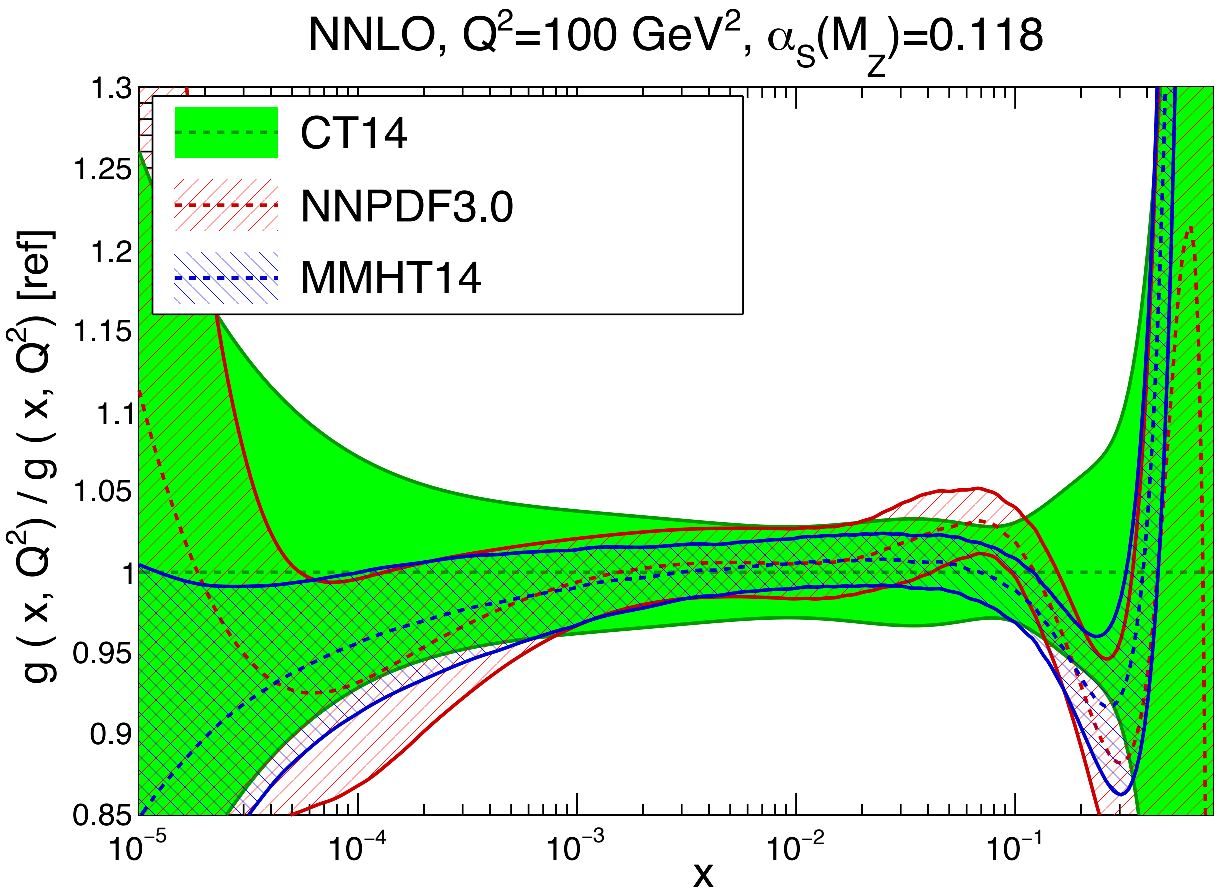
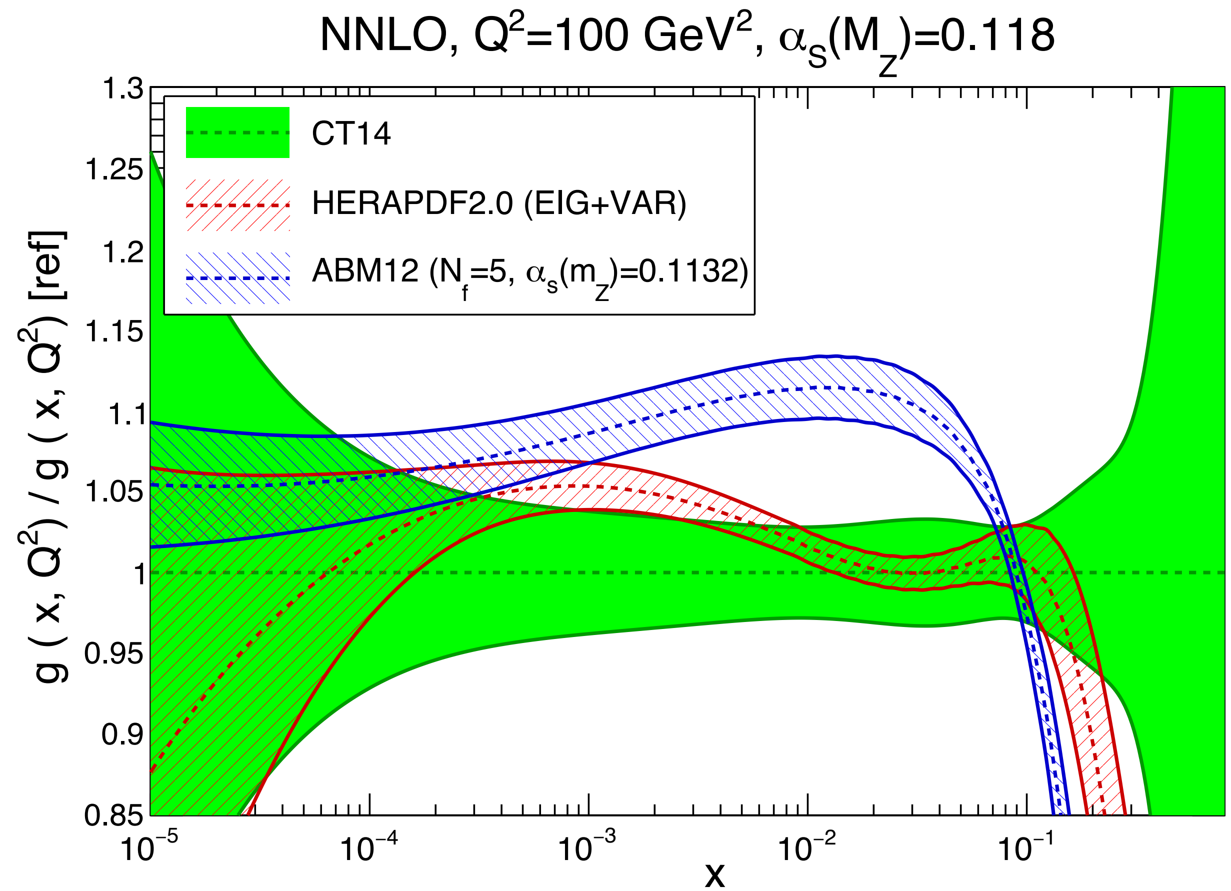




PDF4LHC: combination of 3 global in a single combined PDF set

optimized sets of Hessian eigenvectors or Monte Carlo replicas

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

~ a few hundred sets to produce uncertainty estimates

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

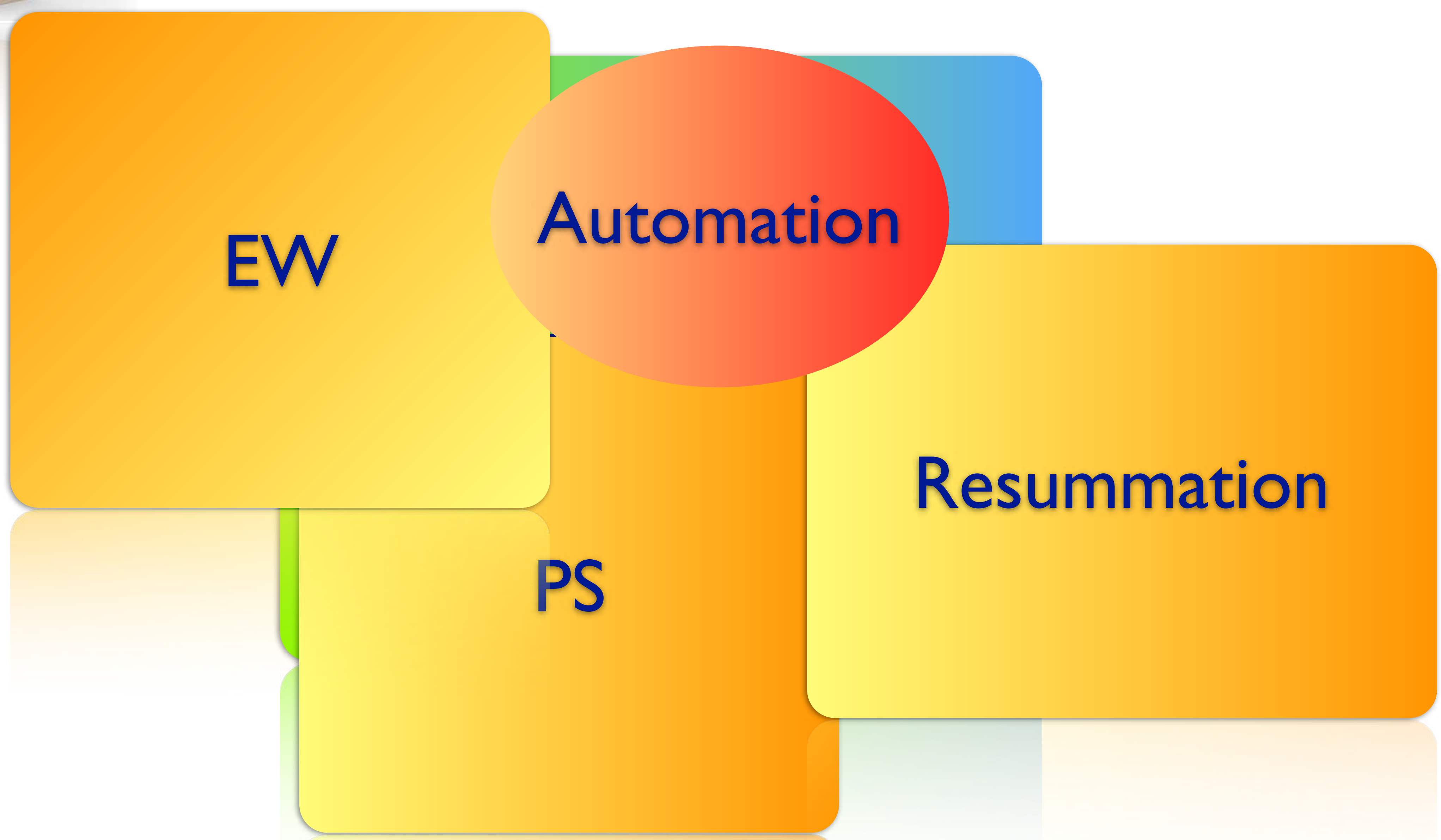
A. Accardi, S. Alekhin, J. Blümlein, M.V. Garzelli, K. Lipka, W. Melnitchouk, S. Moch, R. Placakyte, J.F. Owens, E. Reya, N. Sato, A. Vogt, O. Zenaiev

(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.

New 2019 sets (coming soon) seem to point towards larger uncertainties

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

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

Tree level matrix element — Measurement function — Phase space

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

Fully automated calculations for very large multiplicities

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

✓ Born level: simpler to integrate calculation to parton showers

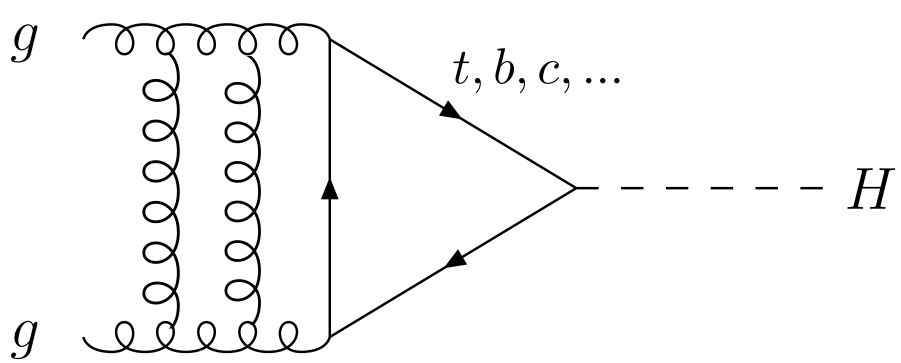
⬇ In most cases, LO not enough for precision physics

Why higher order corrections?

- Large Corrections : check PT
  shape and normalization

$\alpha_s \sim 0.1$ ➡ slow convergence

Higgs production



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

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

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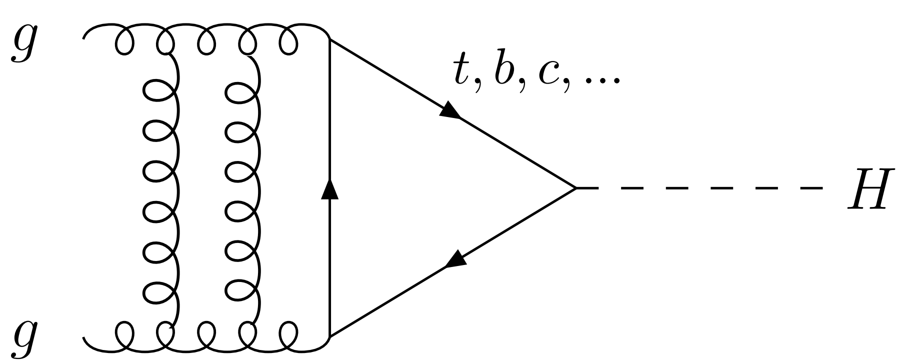
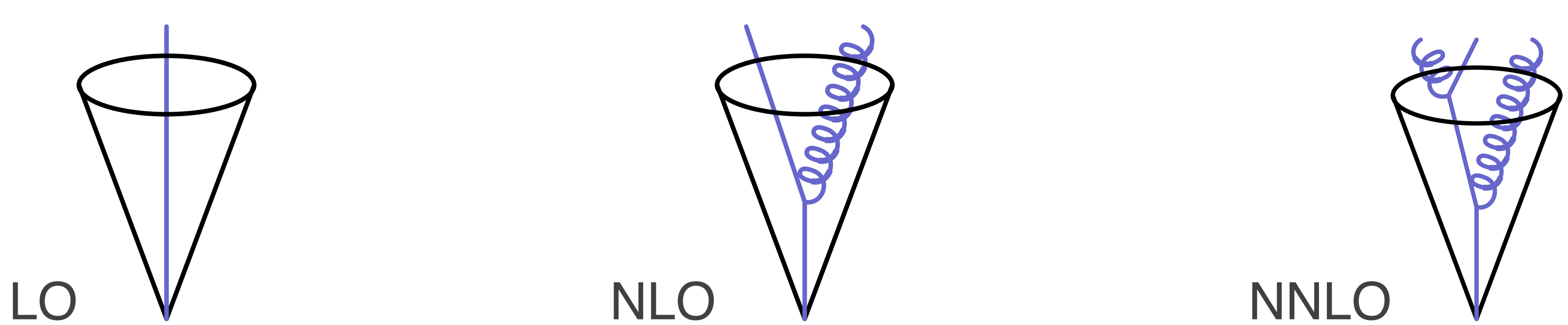


$$C_0\alpha_s^0 + C_1\alpha_s^1 + C_2\alpha_s^2 + C_3\alpha_s^3 + \ldots$$

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

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



Description of jets, transverse momentum, etc

Accurate Theoretical Predictions

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

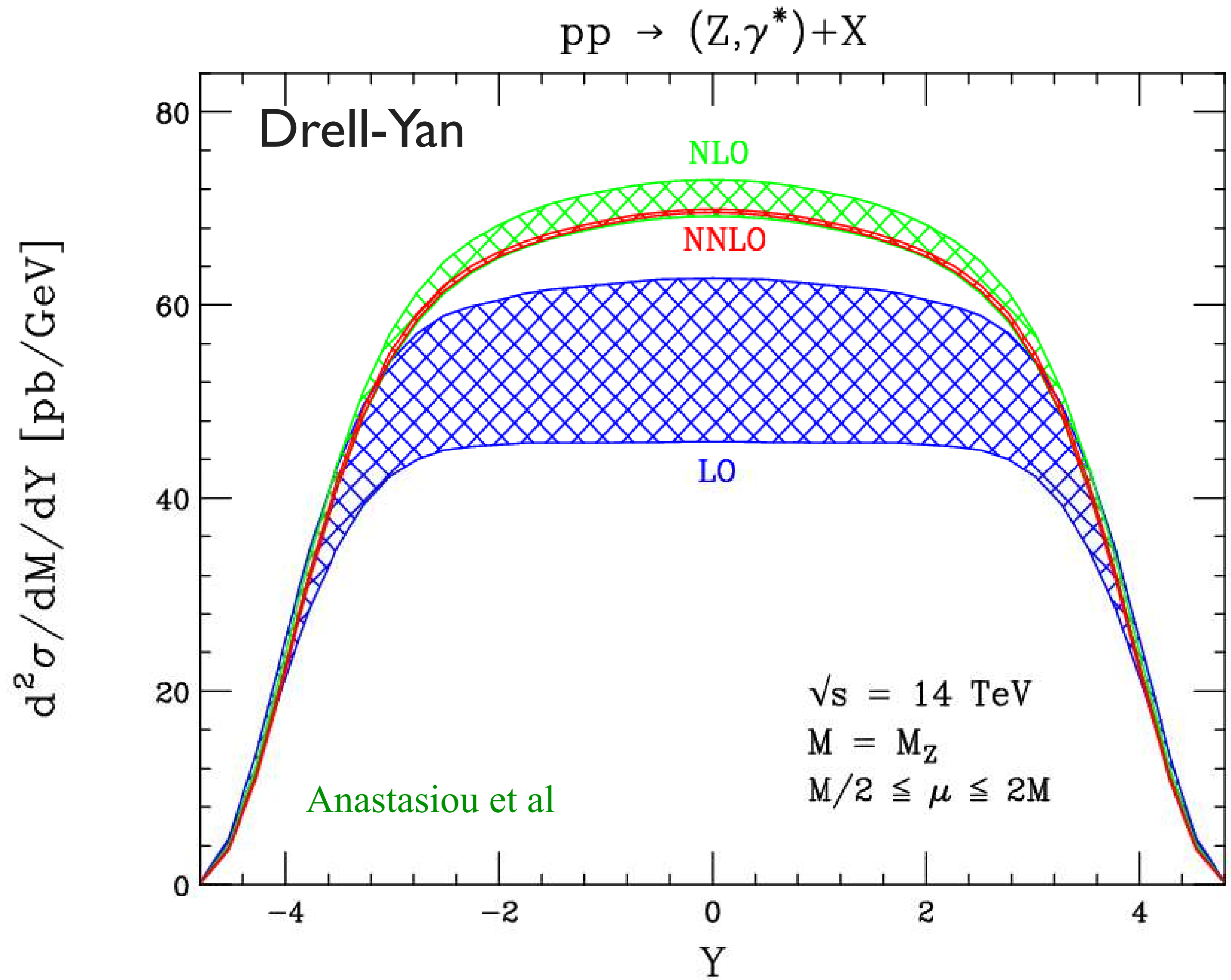
μ_R Renormalization scale

μ_F Factorization scale

- (naive) estimate of size of missing higher orders

Scale dependence considerably reduced at higher orders

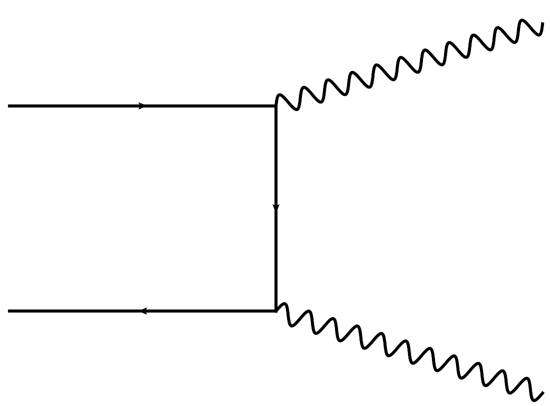
sensible QCD "starts" at NLO



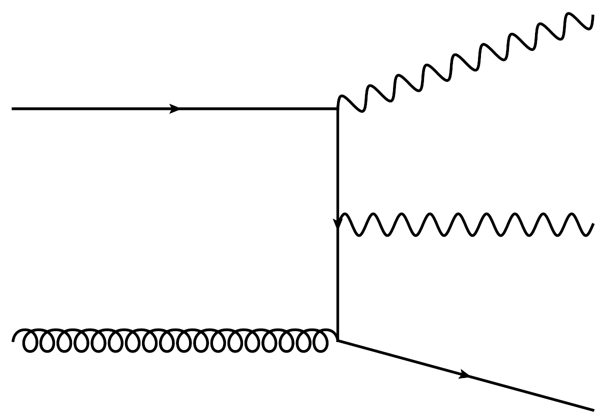
Opening of new channels

Sometimes new channels at higher order provide large corrections due to parton luminosity (pdf, non-perturbative-pertubative interplay)

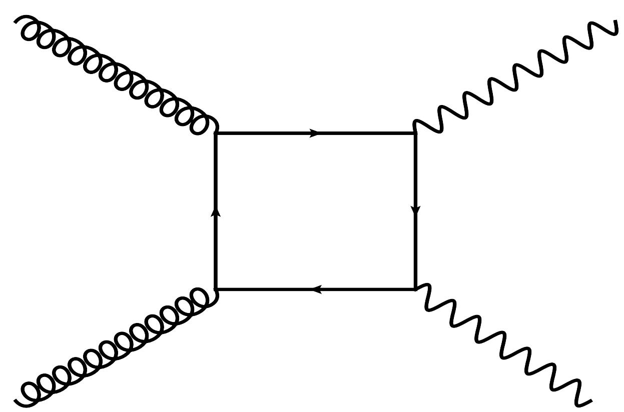
- Diphoton production : main background to Higgs search



$\mathcal{O}(\alpha_s^0)$ but $q\bar{q}$ Luminosity



$\mathcal{O}(\alpha_s)$ but qg Luminosity

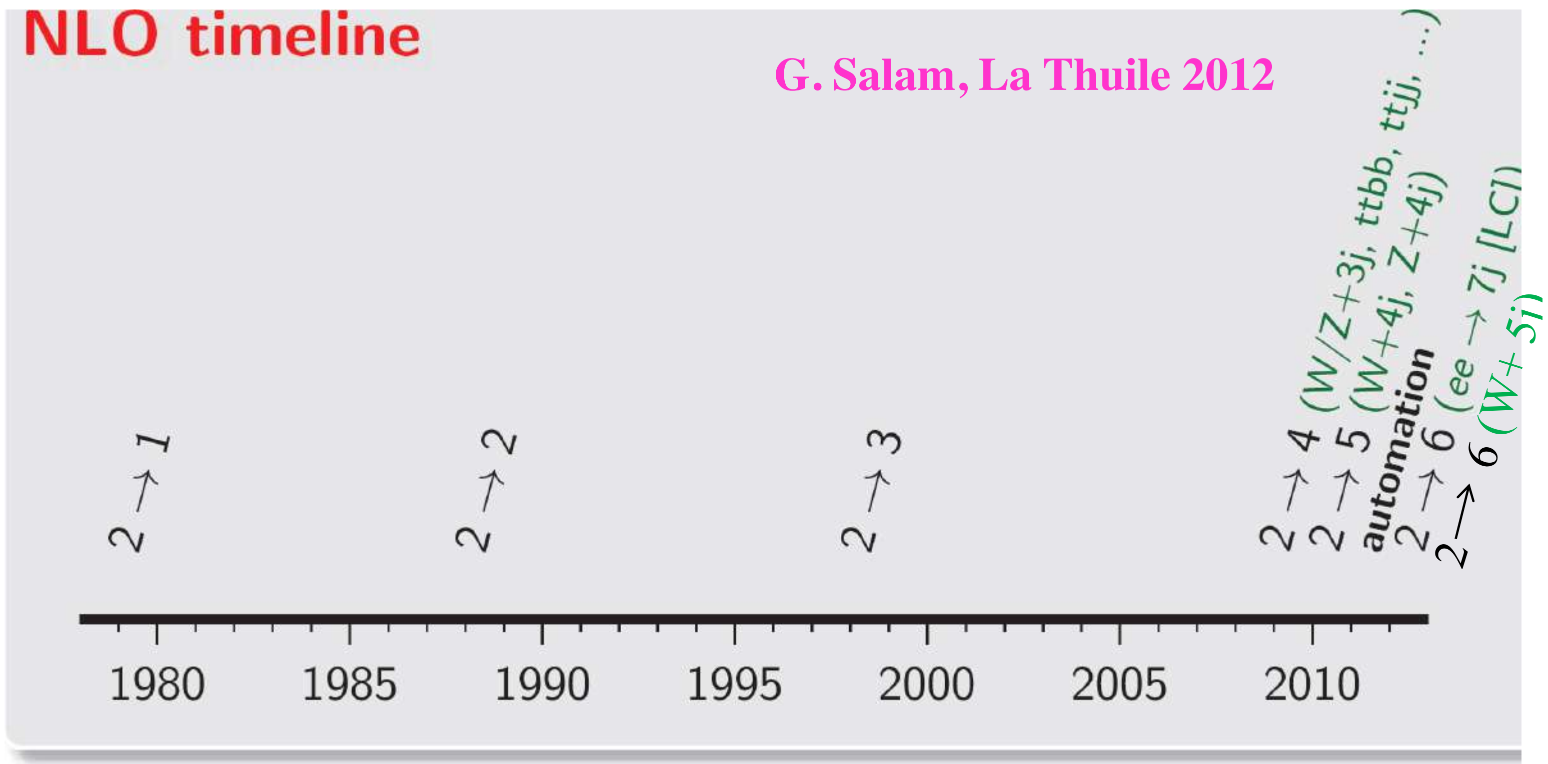


$\mathcal{O}(\alpha_s^2)$ but gg Luminosity

$\gamma\gamma$ production → Box (subset of NNLO) known to be as large as Born!

Dicus, Willenbrock

The NLO revolution



Revolution in calculation of 1-loop amplitudes

- Bottleneck was in the virtual contribution : large multiplicities

- 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
```

$pp \longrightarrow tt+j$

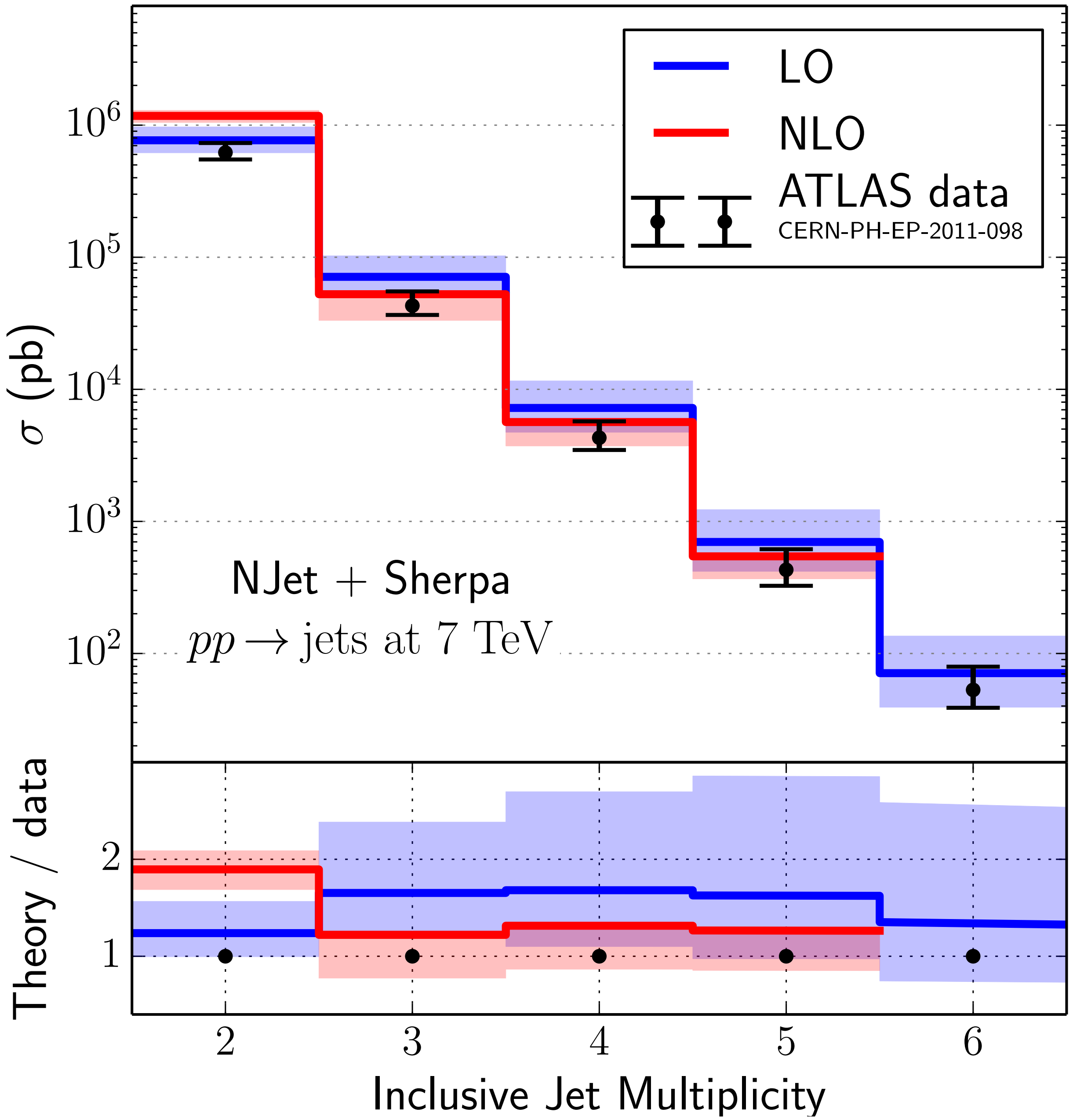
e.g. MadGraph5_aMC@NLO v2.1.1
[Alwall et al. 1405.0301]

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

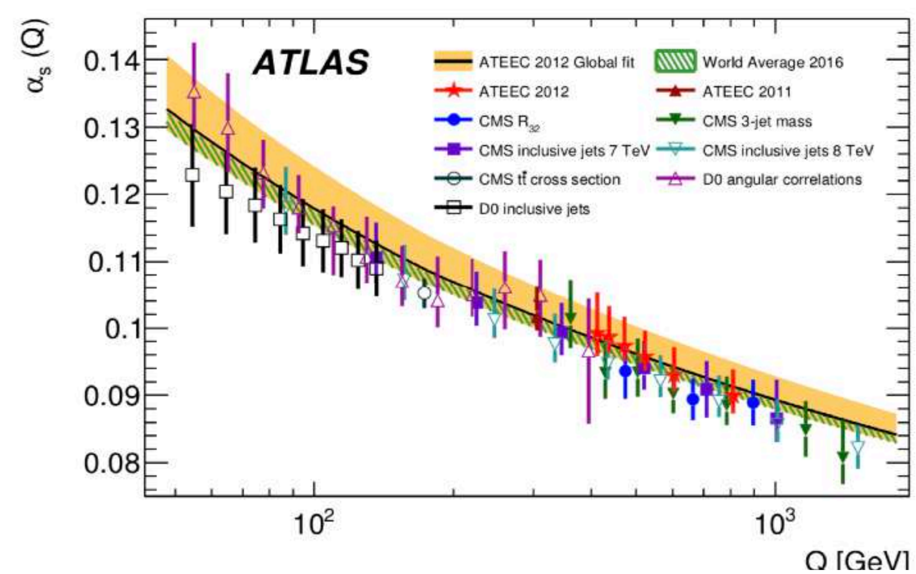


$pp \to 5$ jets at NLO

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

- NLO in very good agreement with data!
- Better stability

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



$$\alpha_s(m_Z) = 0.1162 \pm 0.0011\ (\text{exp.})^{+0.0076}_{-0.0061}\ (\text{scale}) \pm 0.0018\ (\text{PDF}) \pm 0.0003\ (\text{NP})$$

$$\alpha_s(m_Z) = 0.1196 \pm 0.0013\ (\text{exp.})^{+0.0061}_{-0.0013}\ (\text{scale}) \pm 0.0017\ (\text{PDF}) \pm 0.0004\ (\text{NP})$$

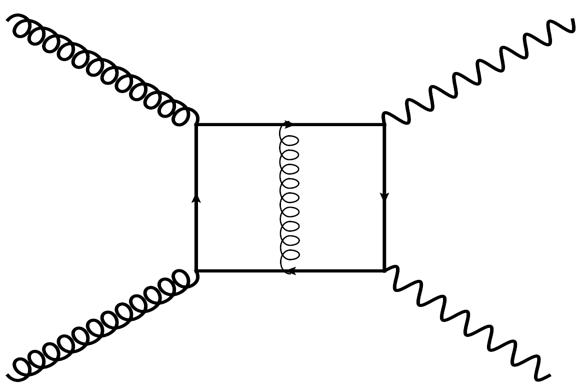
Not everything solved at NLO yet… but constant progress

- 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)

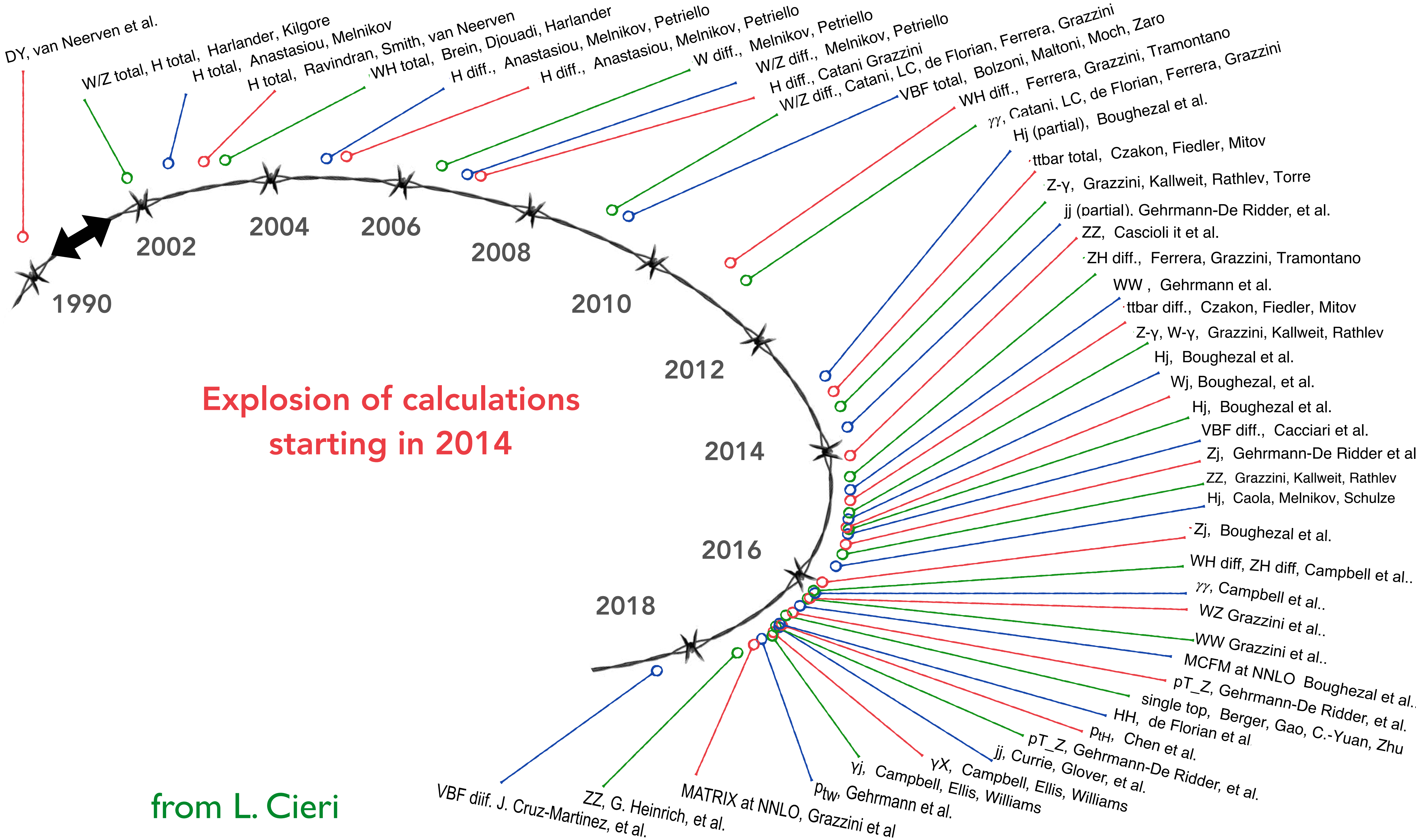
F. Caola, et al (2015-2016)
J. Campbell, K. Ellis, M. Czakon, S. Kirchner (2015)

- BSM (arbitrary, higher dimensional operators, etc)

~Automated!

BSM@NLO+aMC@NLO
MadGolem

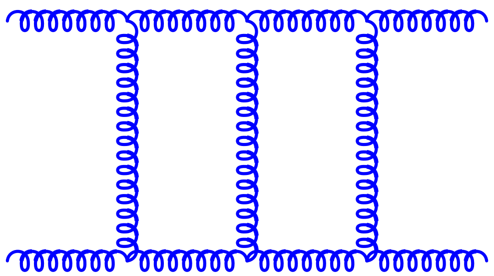
The NNLO revolution

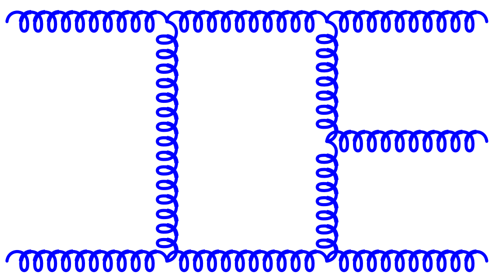


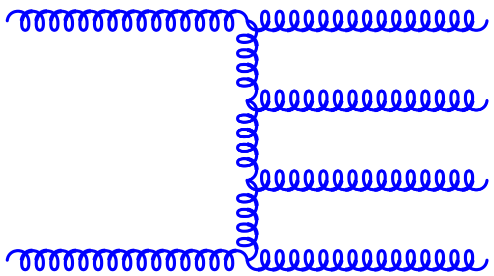
from L. Cieri

Degree of complexity at NNLO

- 2 loop
- 1 loop + single emission
- Double real emission





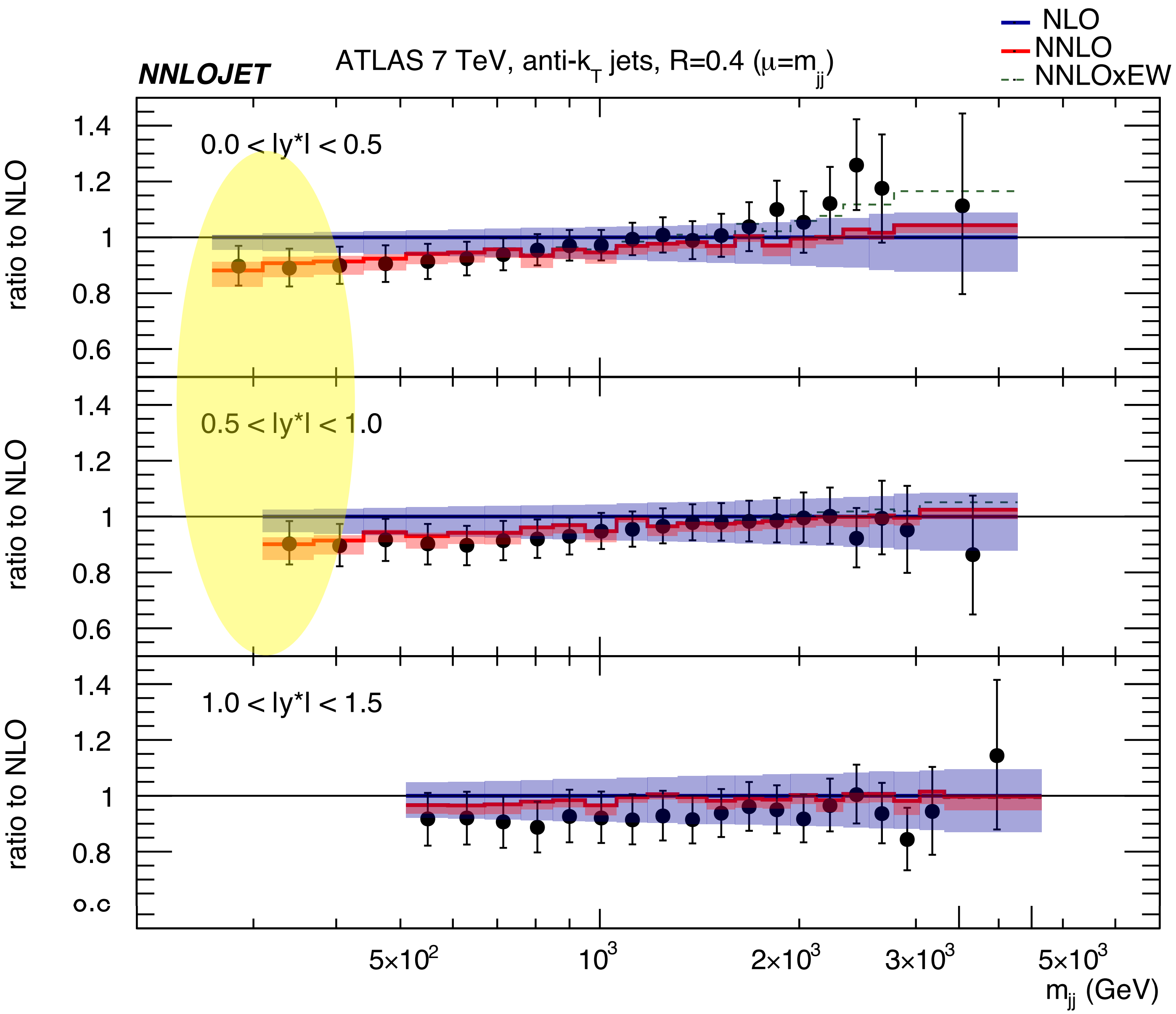


different approaches to deal with divergences

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

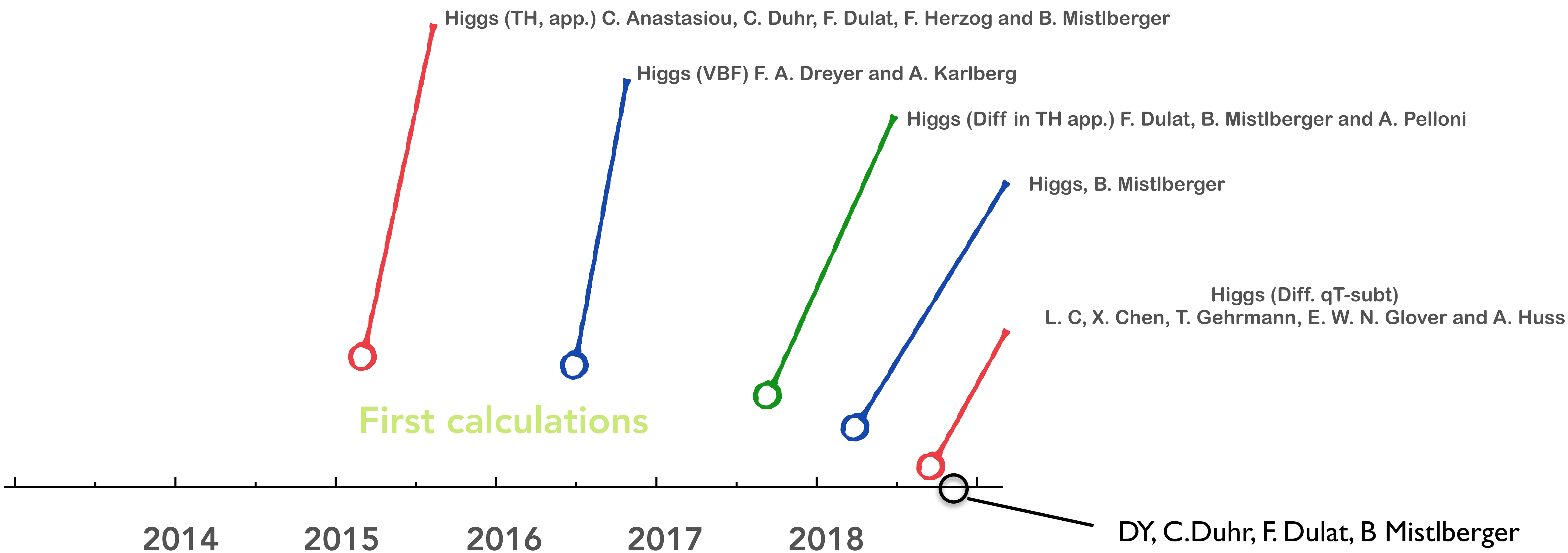
- Moderate NNLO corrections (<10%)
- Improve description of data for low M_{jj}/y^*
- Invariant mass natural scale (better convergence)
- Cures pathological NLO behavior for $\langle p_T \rangle$

$$\mu = m_{jj}$$

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

N^{3}LO

The new Frontier?

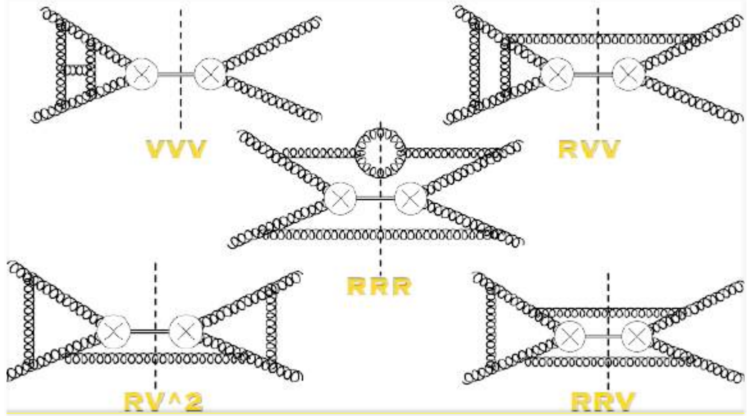


from L. Cieri

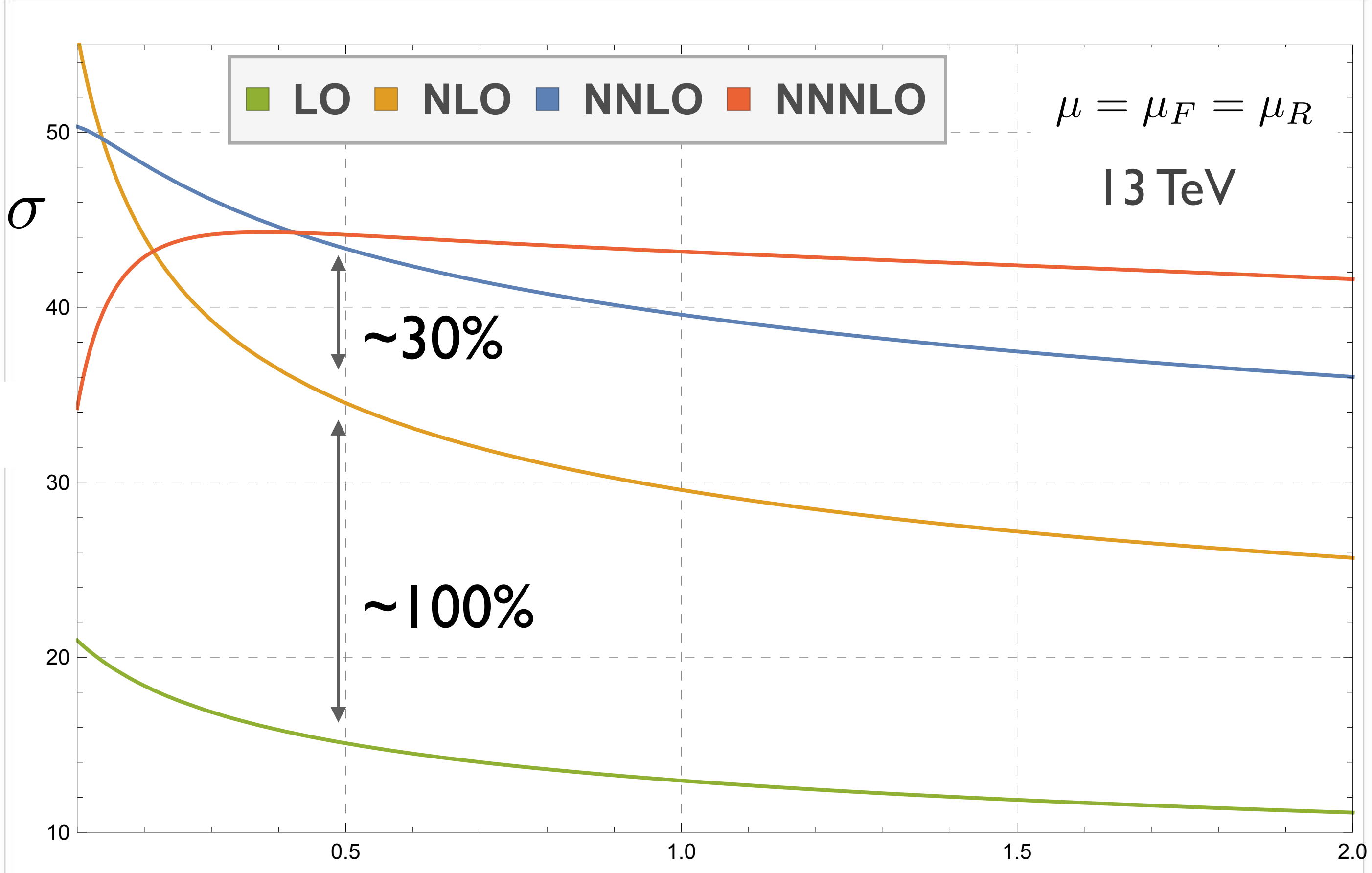
Higgs at N³LO

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



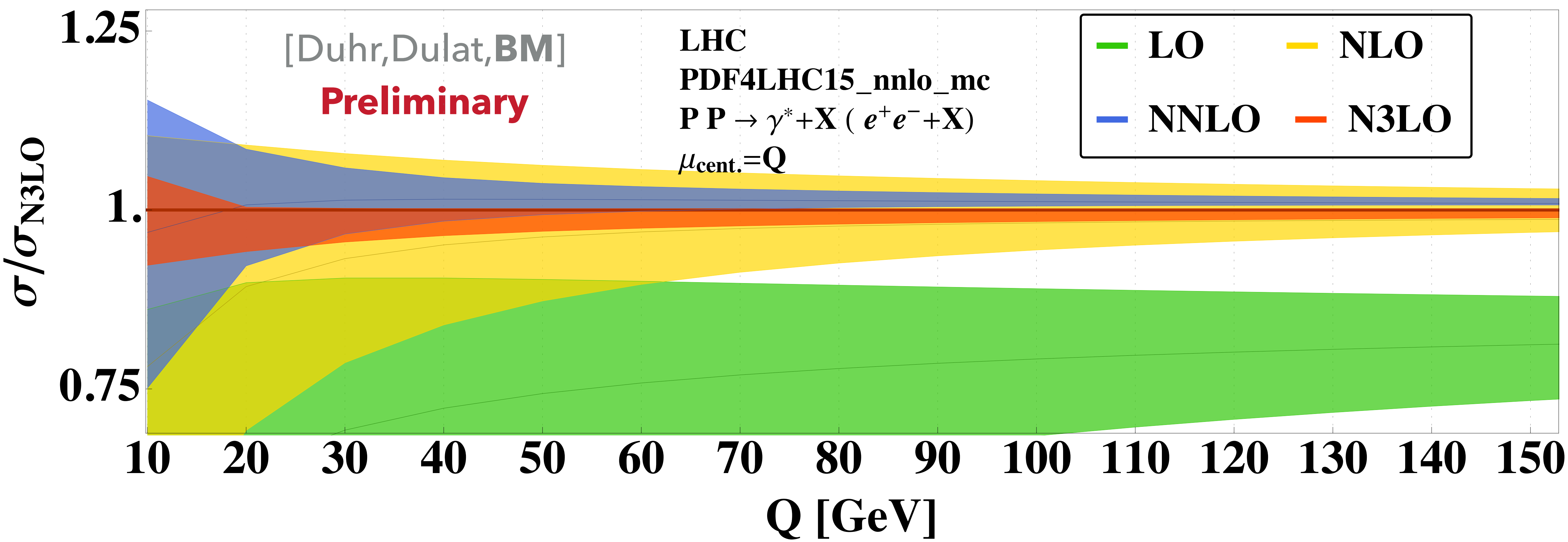
68273802 loop and phase space integrals



- Observe stabilization of expansion
- Small correction (2% at $M_H/2$)
- Scale variation at N³LO ~2%

DRELL-YAN PRODUCTION

C. Duhr, F. Dulat, B. Mistlberger (2019)



Currently no N3LO PDFs

- Currently only photon exchange.
- Interesting perturbative development!
- N3LO outside of NNLO scale band.
- Setting scales and / or using them for uncertainty estimates is tricky.

DRELL-YAN PRODUCTION

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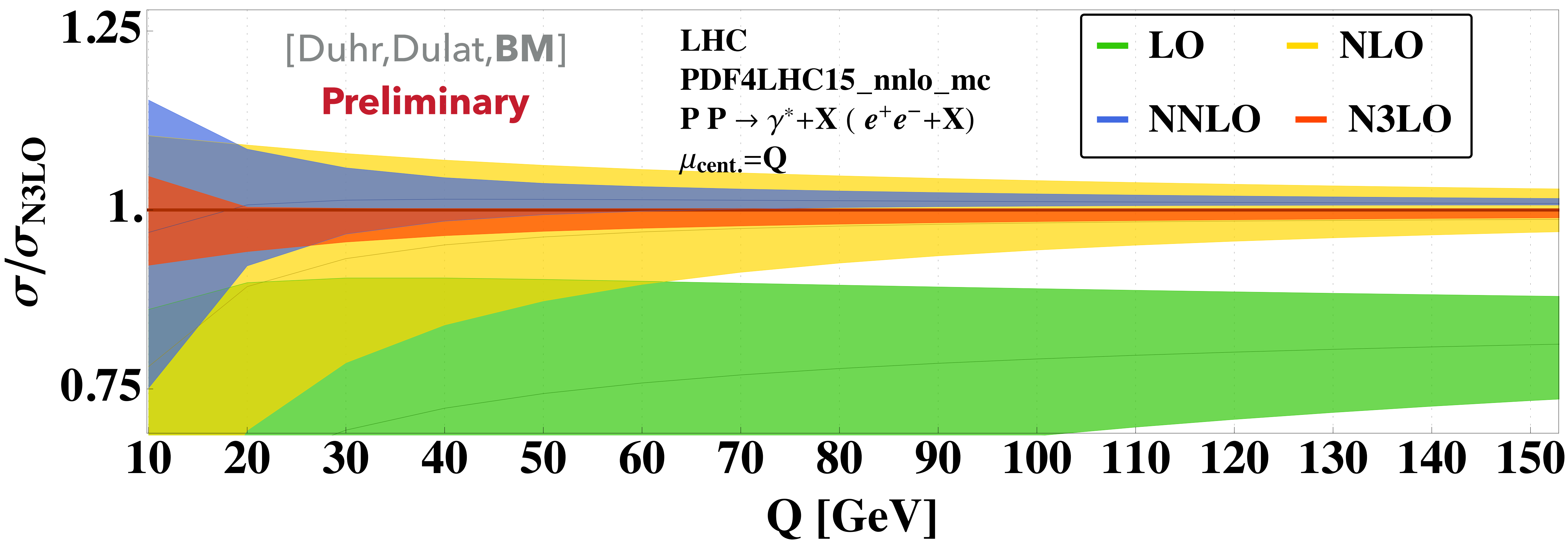

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Currently no N3LO PDFs

N^{3}LO Splitting functions

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

Conclusions

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

  Automation of NLO
  Several NNLO processes $2 \to 2$ ✓
  Even N³LO 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)

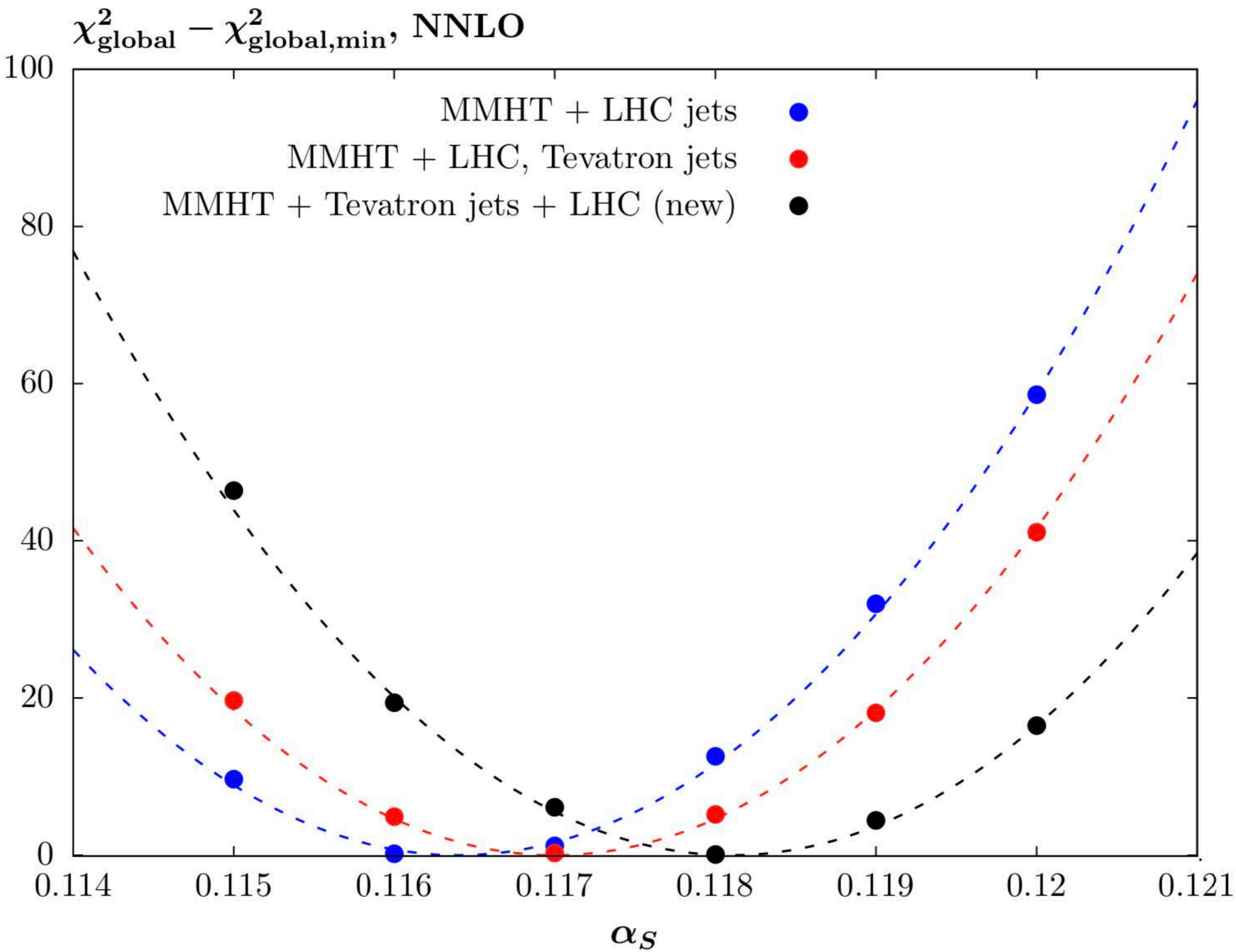
  Will need significant development

- Need a more rigorous treatment of TH uncertainties

High Precision@ Large Hard Calculations

T.Binoth

Backup slides


$\chi^2_{\mathrm{global}} - \chi^2_{\mathrm{global,min}}$, NNLO
MMHT + LHC jets
MMHT + LHC, Tevatron jets
MMHT + Tevatron jets + LHC (new)
100
80
60
40
20
0
0.114
0.115
0.116
0.117
0.118
0.119
0.12
0.121
α_S

Why so complicated?

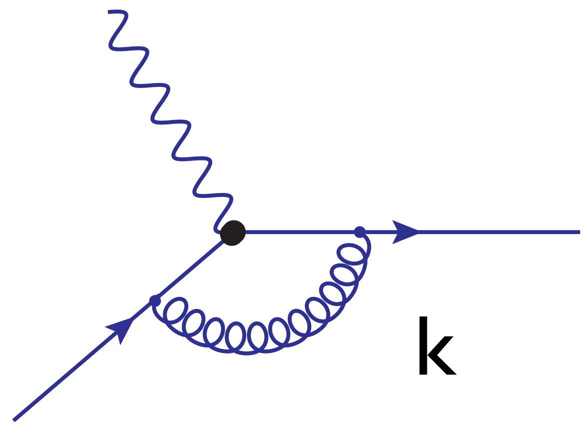
Blame Feynman!

- Real and virtual contributions : separately divergent

UV

$$\int_0^{\infty} dk$$

IR



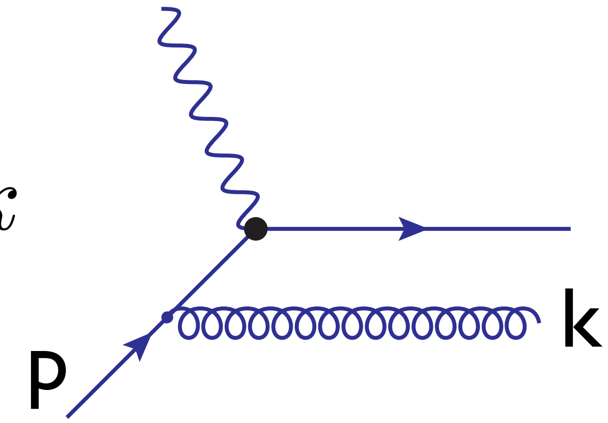
1 loop

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

$\epsilon = d - 4$

+

$$\int dk$$



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

1 extra parton

IR in soft/collinear configurations

- Real contribution : singularity, integration, subtraction
- Virtual contribution : technical problems (large multiplicities)

Handling singularities $\int |M_R|^2 dPS$

Subtraction Method : need local subtraction counter-term

$$\underbrace{\int_0^1 (|M_R|^2 - \mathcal{S}) dPS}_{\text{Finite}} + \underbrace{\int \mathcal{S}\, dPS + \int |M_V|^2 dPS'}_{\text{Computed "analytically" cancel divergences}}$$

Phase space slicing : split phase space according to singular configurations

$$\underbrace{\int_\delta^1 |M_R|^2 dPS}_{\text{Regularized by cut-off (numerically involved)}} + \underbrace{\int_0^\delta |M_R|^2 dPS + \int |M_V|^2 dPS'}_{\text{Can be obtained from resummation framework/computed}}$$

Towards automation @ NNLO

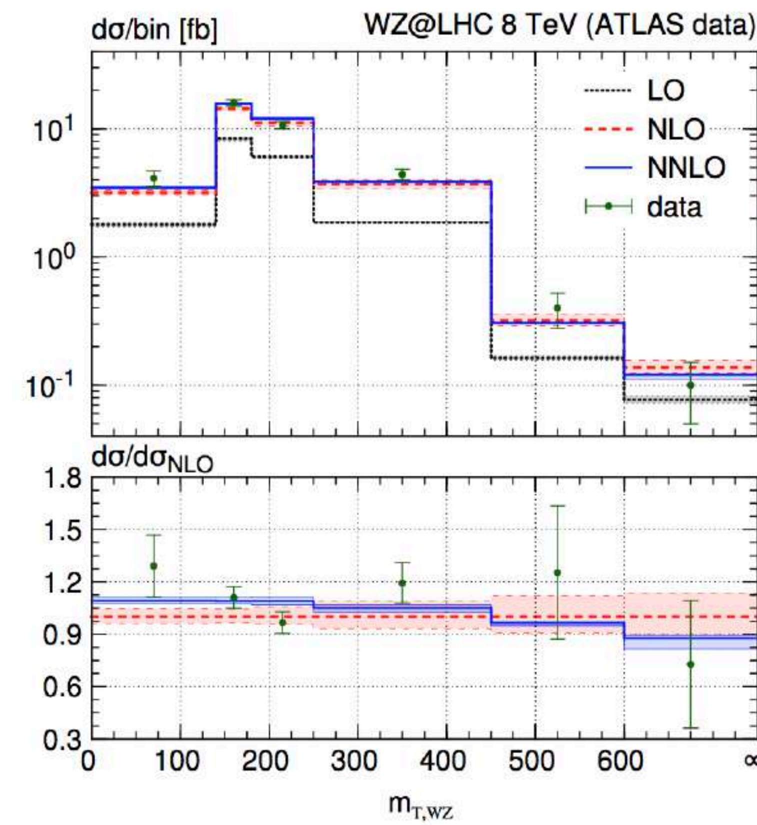
Matrix @ NNLO

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



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

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

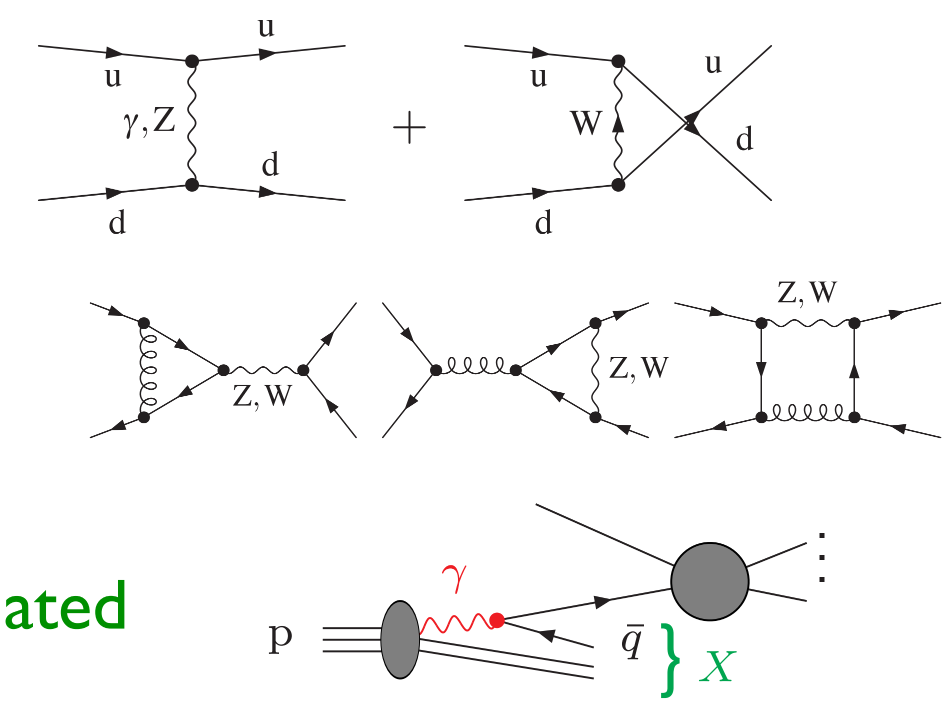
Dijet production

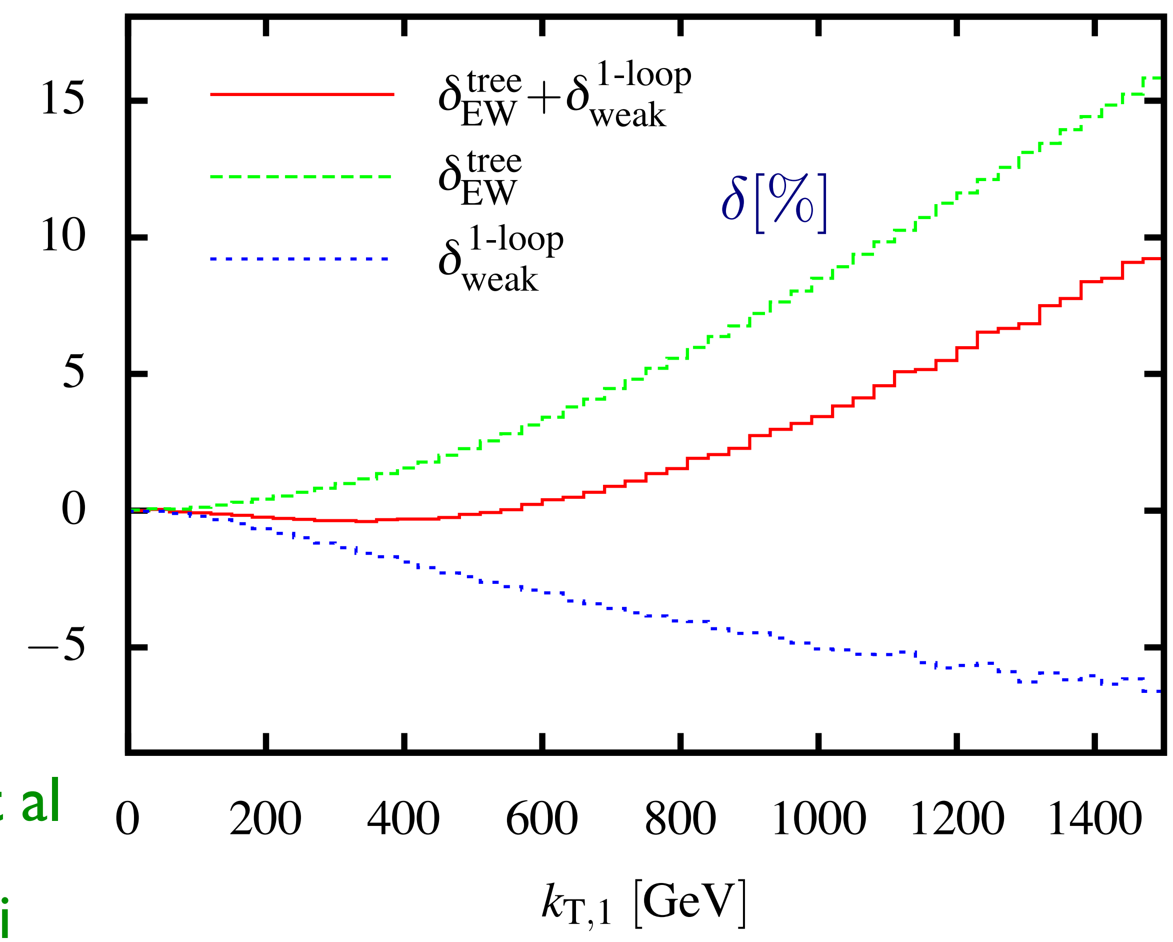
Dittmaier, Huss, Speckner

tree EW

1-loop EW

photon initiated

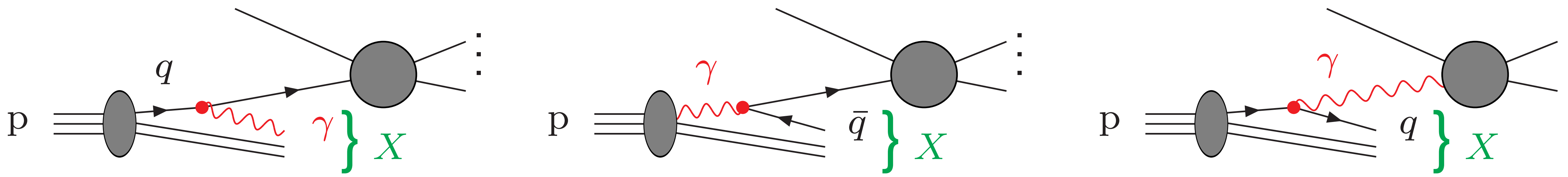




LUXqed :photon content of the proton Manohar et al

QED-QCD splitting functions DdeF, Rodrigo, Sborlini

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)

TH Uncertainties

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

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

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

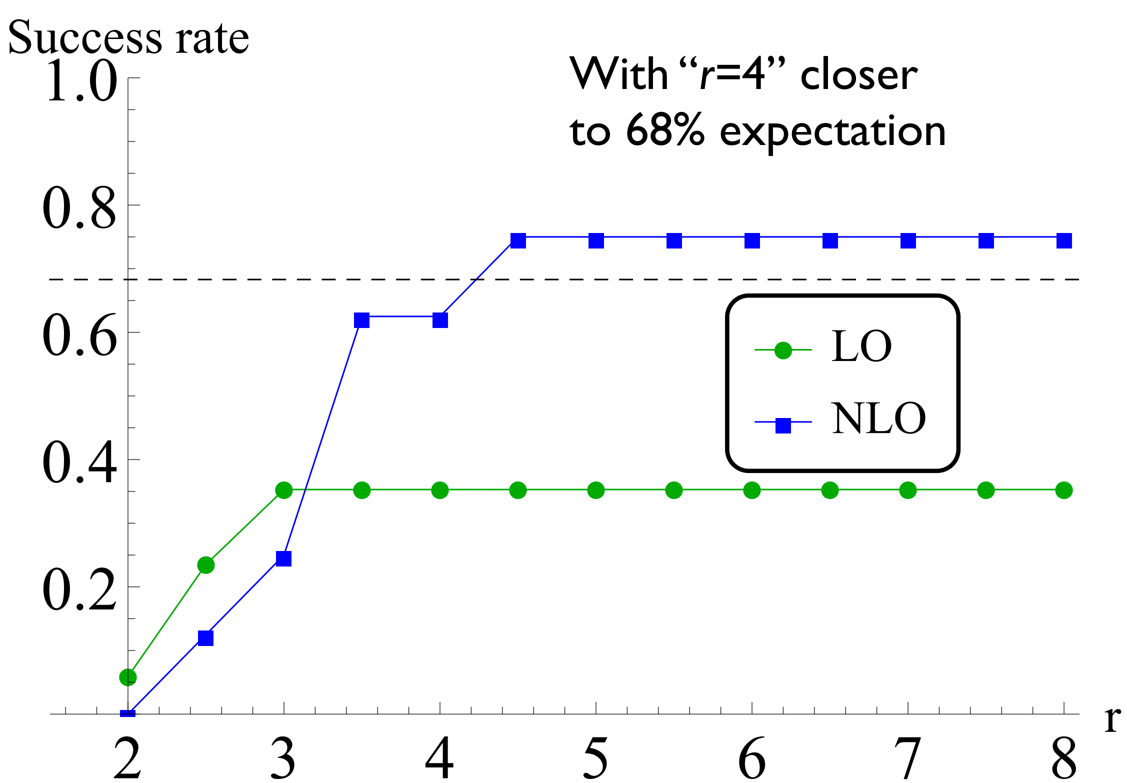
- Lack of probabilistic framework : how to combine with other?

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

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

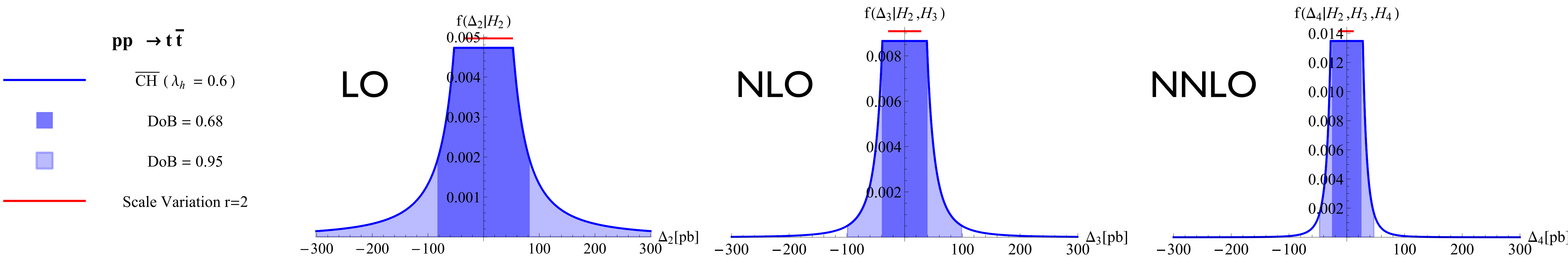
    E. Bagnaschi, M. Cacciari, A. Guffanti, L. Jenniches (2014)

  - 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)



- a rescaling factor of 3-4 appears more likely to estimate missing higher orders consistent with a 68%-heuristic CL interpretation

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

Evaluate "higher order" terms from resummation framework

DdeF, J. Mazzitelli, S. Moch, A. Vogt (2014)
R. Ball et al (2013)

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