Theory Higgs Production

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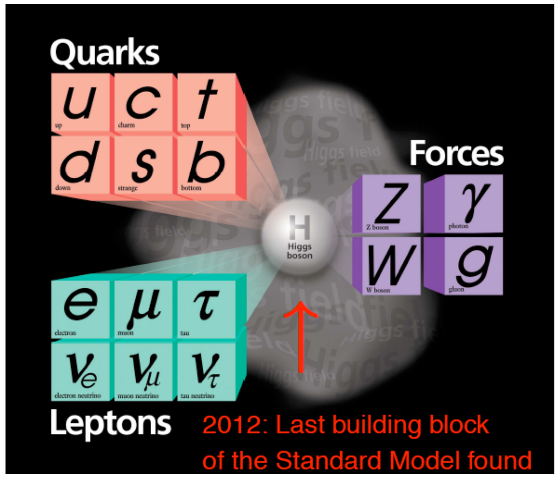
Higgs Hunting 2016, August 31, LPNHE Paris

In the Last Four Years…

- 2012: LHC discovered a Higgs boson, it appears to be SM-like



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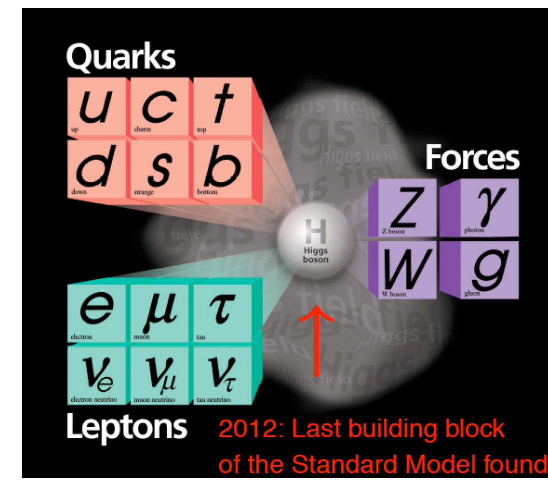

- 2015: LHC Run II starts. With an energy increase to 13 TeV and a luminosity goal of 300fb^{-1}, the discovery potential is significantly enhanced.

2015

theguardian

Large Hadron Collider Restart: Live Blog

Easter morning excitement as the CERN accelerator team send beams around the LHC for the first time in many months - a major milestone on the way to even higher energy collisions!

(05-Apr-2015 10:40:17)

All collimators open
Circulating beam 2

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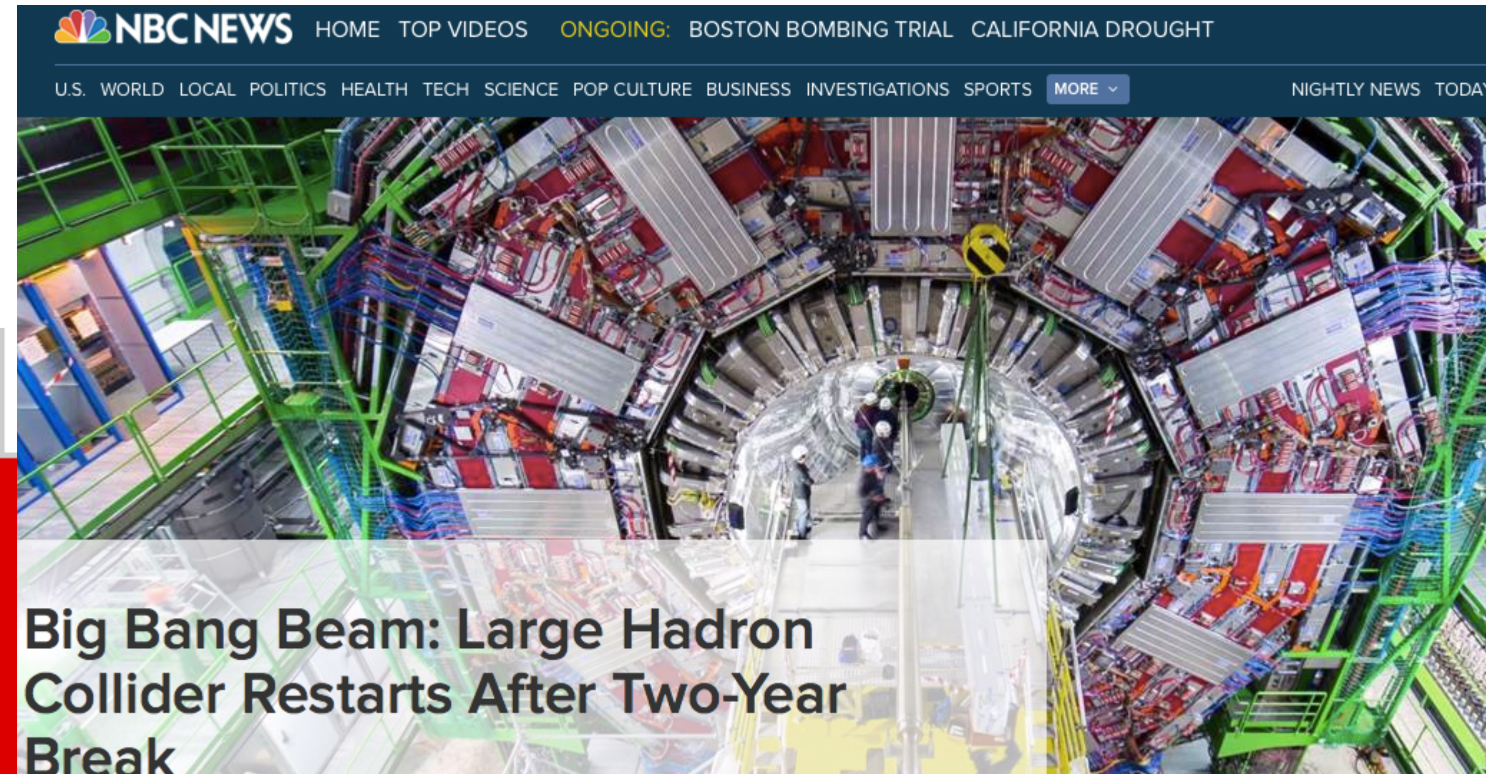
Large Hadron Collider: World's biggest physics experiment restarts



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LHC restart: 'We want to break physics'

So what does it take to break physics?

So what does it take to break physics?

Direct searches:
find new particles

Indirect searches:
find deviations from
the SM behavior

So what does it take to break physics?

- In the absence of convincing evidence of new physics, precision searches for subtle deviations from the SM are vital. Possible with the high energy and luminosity of LHC Run II.
- Percent experimental precision requires a matching theory precision!

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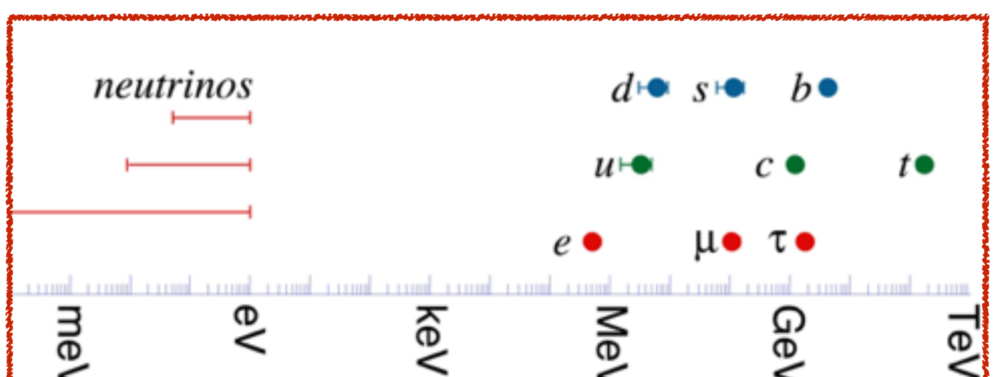
The Higgs is the likeliest place to look, as its properties are connected to the puzzles of the SM

The flavor puzzle: what explains the observed masses and mixing, which come from Higgs couplings?



Hierarchy problem: no symmetry prevents the Higgs mass from receiving quadratic divergences, unlike for other particles

$$M^{gauge,ferm} \sim M^{bare}\{1 + a \ln \Lambda/M\}$$

$$(M^{Higgs})^2 \sim (M^{bare})^2 + \Lambda^2$$

So what does it take to break physics?

- In the absence of convincing evidence of new physics, precision searches for subtle deviations from the SM are vital. Possible with the high energy and luminosity of LHC Run II.
- Percent experimental precision requires a matching theory precision!

Constructing a new theory of Nature is intimately connected to understanding the Higgs properties. Progress on the theory side is a major contributor to this!

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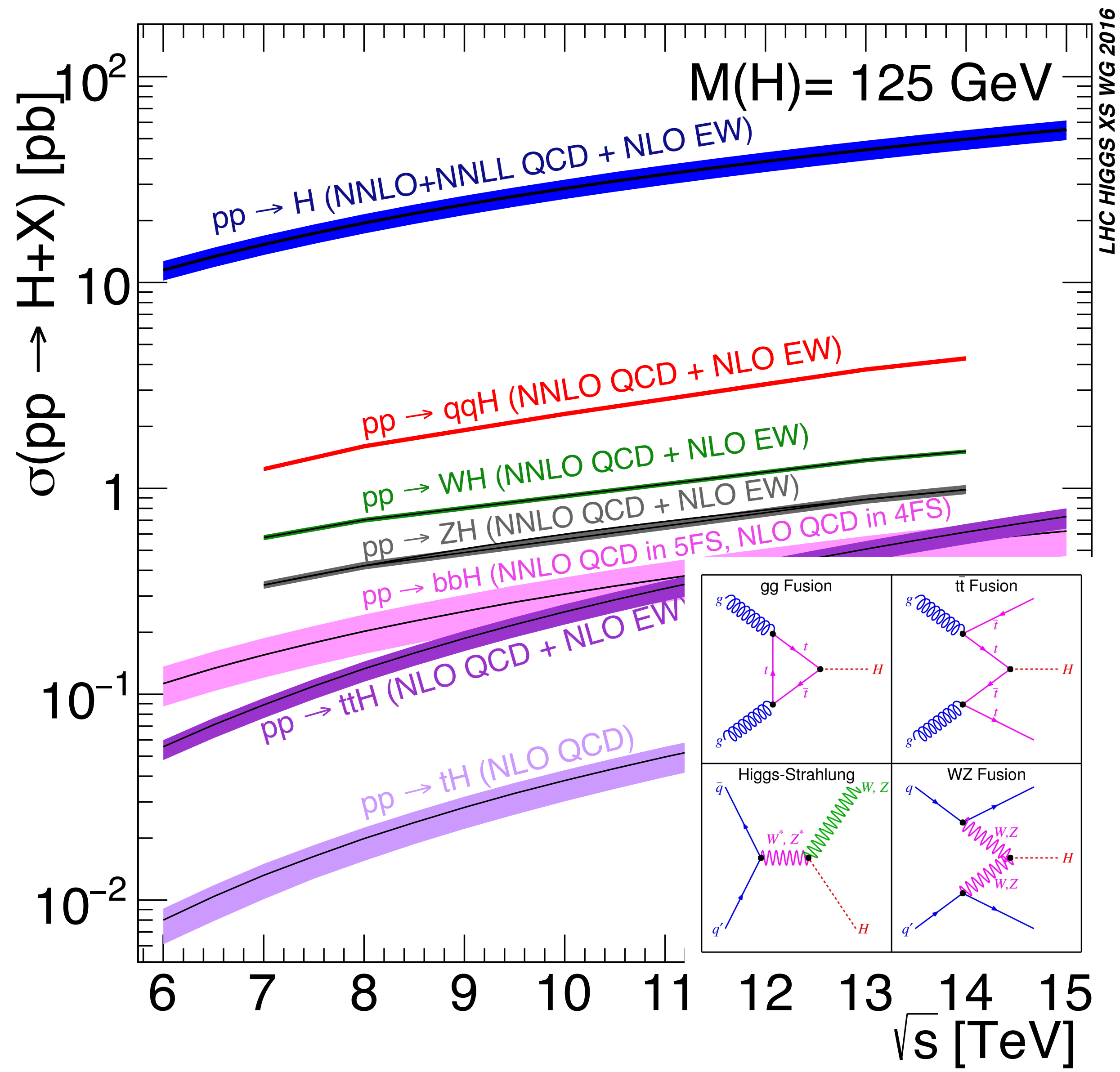
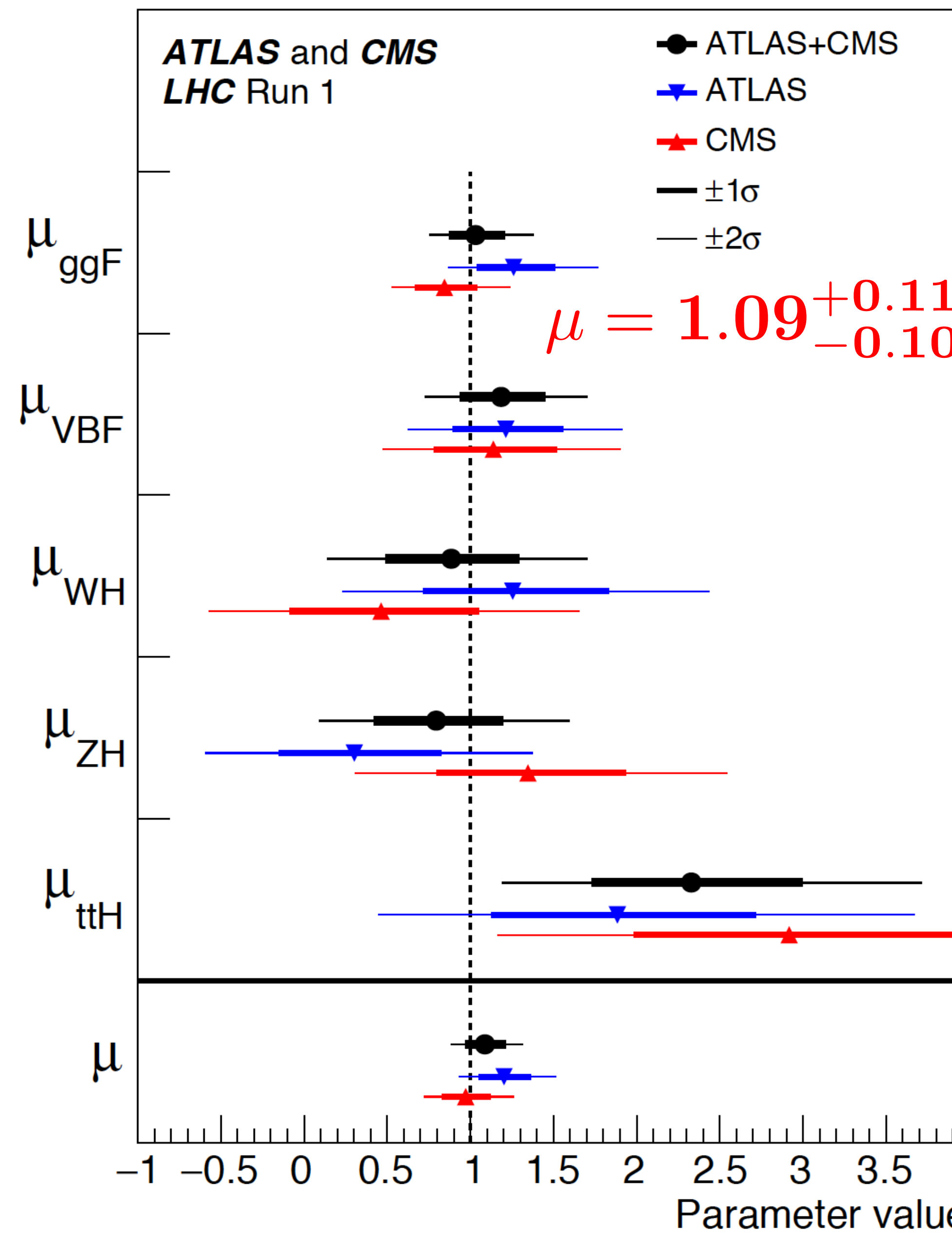
$$(M^{Higgs})^2 \sim (M^{bare})^2 + \Lambda^2$$

this is a limited selection of topics and is by no means complete. I apologize in advance for any omissions!

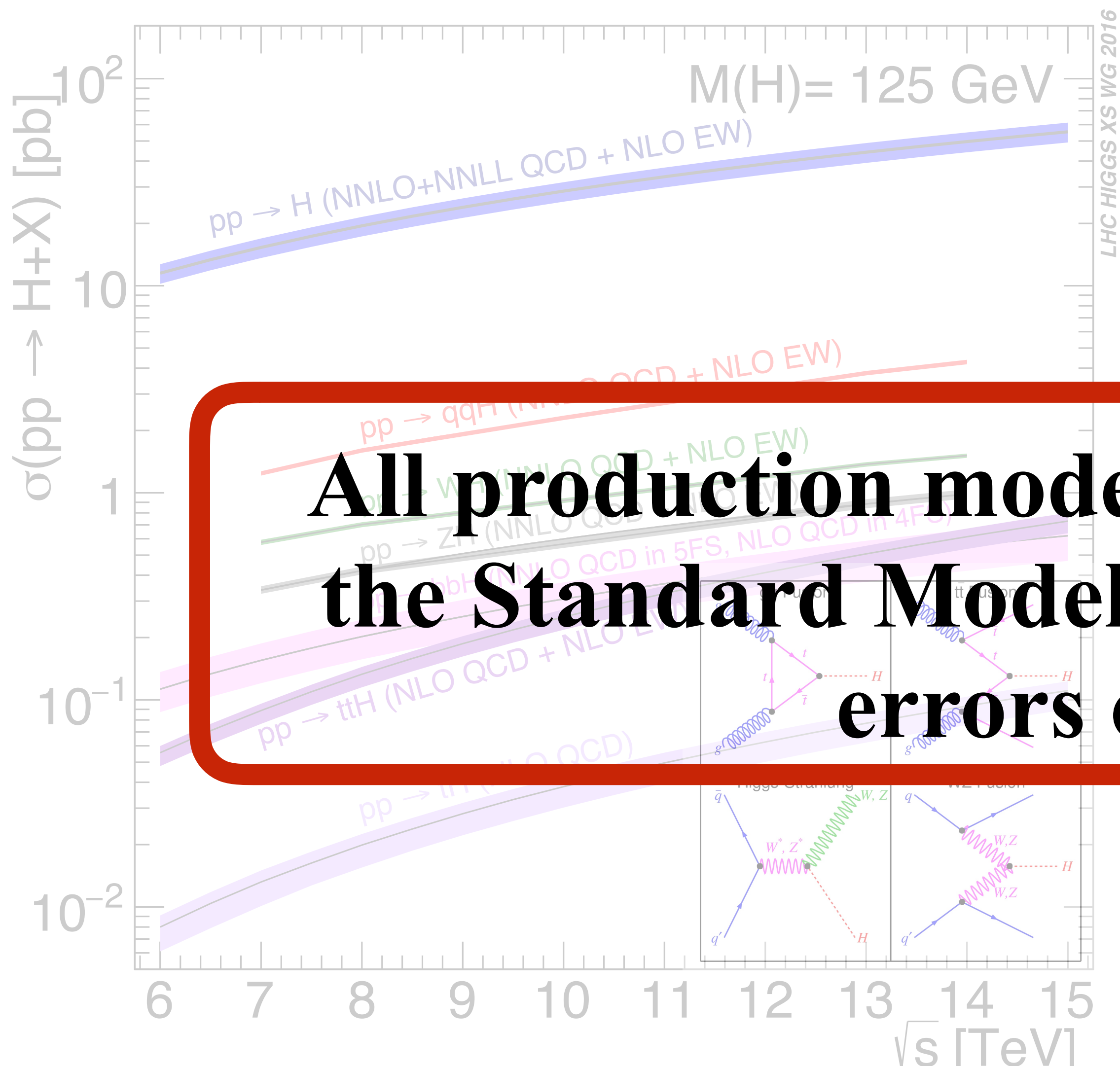
Overview of Higgs Production in SM

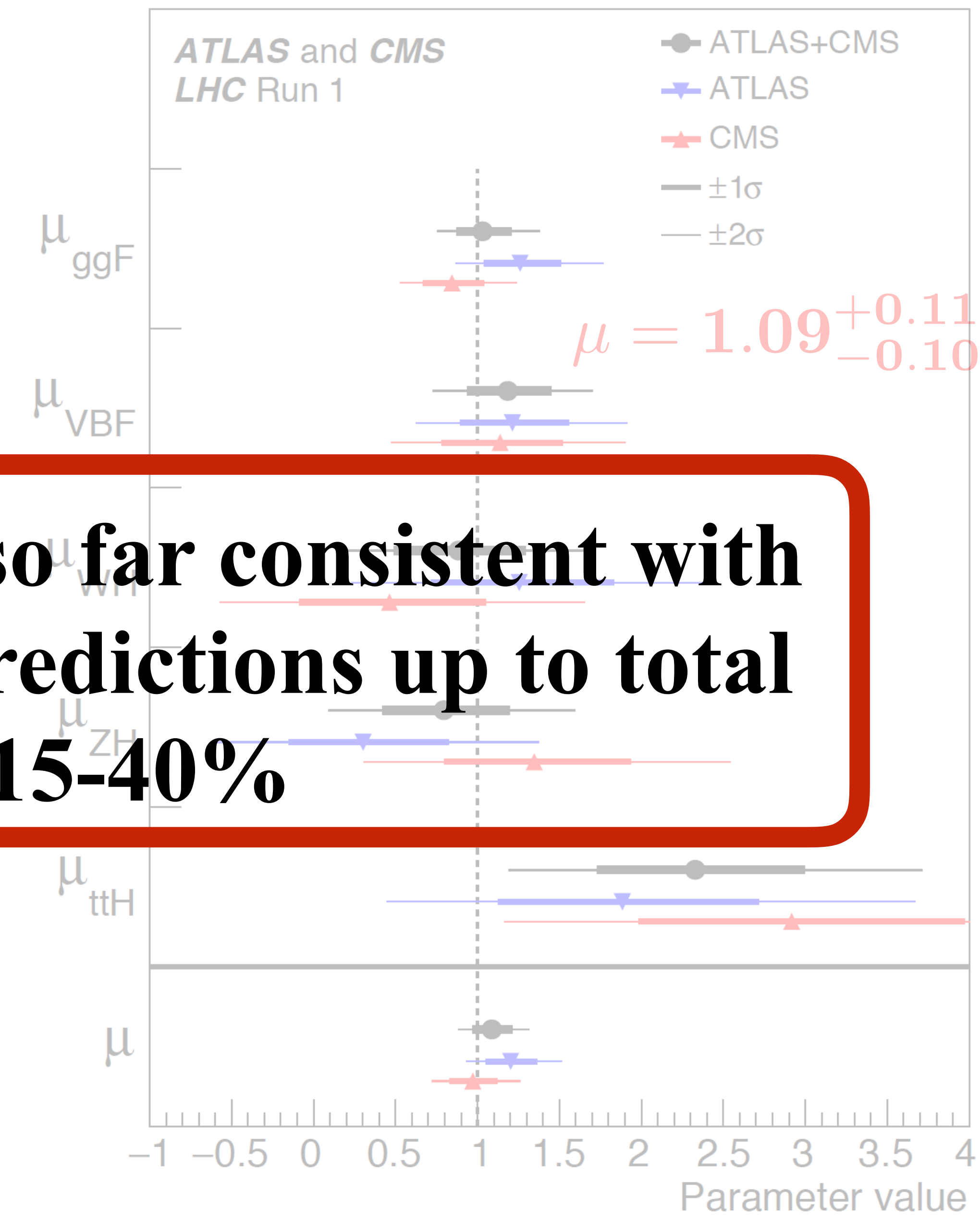




- Major production processes at the LHC are gluon fusion and vector boson fusion.

Overview of Higgs Production in SM





All production modes so far consistent with the Standard Model predictions up to total errors of 15-40%

- Major production processes at the LHC are gluon fusion and vector boson fusion.

LHC Run 1 & Theory

$H \to ZZ^*$

ATLAS

Source of uncertainty	4μ	$2e2\mu$	$2\mu 2e$	$4e$	combined
Electron reconstruction and identification efficiencies	–	1.7%	3.3%	4.4%	1.6%
Electron isolation and impact parameter selection	–	0.07%	1.1%	1.2%	0.5%
Electron trigger efficiency	–	0.21%	0.05%	0.21%	<0.2%
$\ell\ell + ee$ backgrounds	–	–	3.4%	3.4%	1.3%
Muon reconstruction and identification efficiencies	1.9%	1.1%	0.8%	–	1.5%
Muon trigger efficiency	0.6%	0.03%	0.6%	–	0.2%
$\ell\ell + \mu\mu$ backgrounds	1.6%	1.6%	–	–	1.2%
QCD scale uncertainty					6.5%
PDF, α_s uncertainty					6.0%
$H \to ZZ^*$ branching ratio uncertainty					4.0%

LHC Run 1 & Theory

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$H \to WW^*$

Observed $\mu = 1.09$

Source	Error +	Error −
Data statistics	0.16	0.15
Signal regions	0.12	0.12
Profiled control regions	0.10	0.10
Profiled signal regions	-	-
MC statistics	0.04	0.04
Theoretical systematics	0.15	0.12
Signal $H \to WW^*$ $\mathcal{B}$	0.05	0.04
Signal ggF cross section	0.09	0.07
Signal ggF acceptance	0.05	0.04
Signal VBF cross section	0.01	0.01
Signal VBF acceptance	0.02	0.01
Background WW	0.06	0.06
Background top quark	0.03	0.03
Background misid. factor	0.05	0.05
Others	0.02	0.02
Experimental systematics	0.07	0.06
Background misid. factor	0.03	0.03
Bkg. $Z/\gamma^* \to ee, \mu\mu$	0.02	0.02
Muons and electrons	0.04	0.04
Missing transv. momentum	0.02	0.02
Jets	0.03	0.02
Others	0.03	0.02
Integrated luminosity	0.03	0.03
Total	0.23	0.21

Plot of error (scaled by 100): -30 -15 0 15 30

LHC Run 1 & Theory

ATLAS

$H \rightarrow ZZ^*$

Source of uncertainty		$4e$	combined
Electron reconstruction and …	…	4.4%	1.6%
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Muon recon…			…5%
Muon trigge…			…2%
$\ell\ell + \mu\mu$ bac…			…2%
QCD scale …			…5%
PDF, α_s un…			…0%
$H \rightarrow ZZ^*$ b…			…0%

$H \rightarrow WW^*$

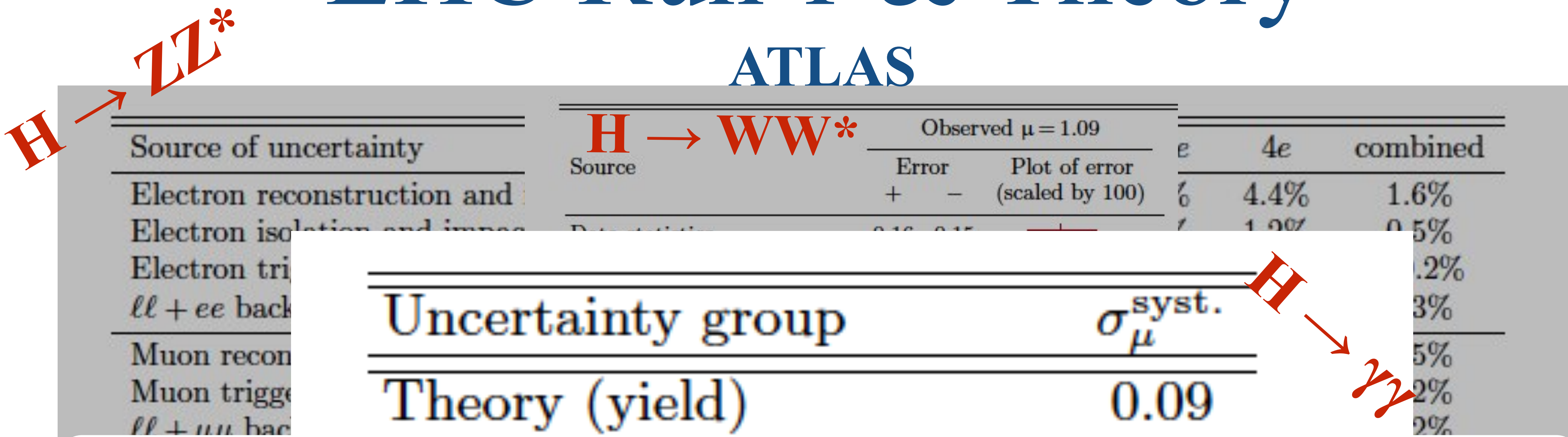
Source	Observed $\mu = 1.09$		
	Error +	Error −	Plot of error (scaled by 100)

$H \rightarrow \gamma\gamma$

Uncertainty group	$\sigma_{\mu}^{\text{syst.}}$
Theory (yield)	0.09
Experimental (yield)	0.02
Luminosity	0.03
MC statistics	< 0.01
Theory (migrations)	0.03
Experimental (migrations)	0.02
Resolution	0.07
Mass scale	0.02
Background shape	0.02

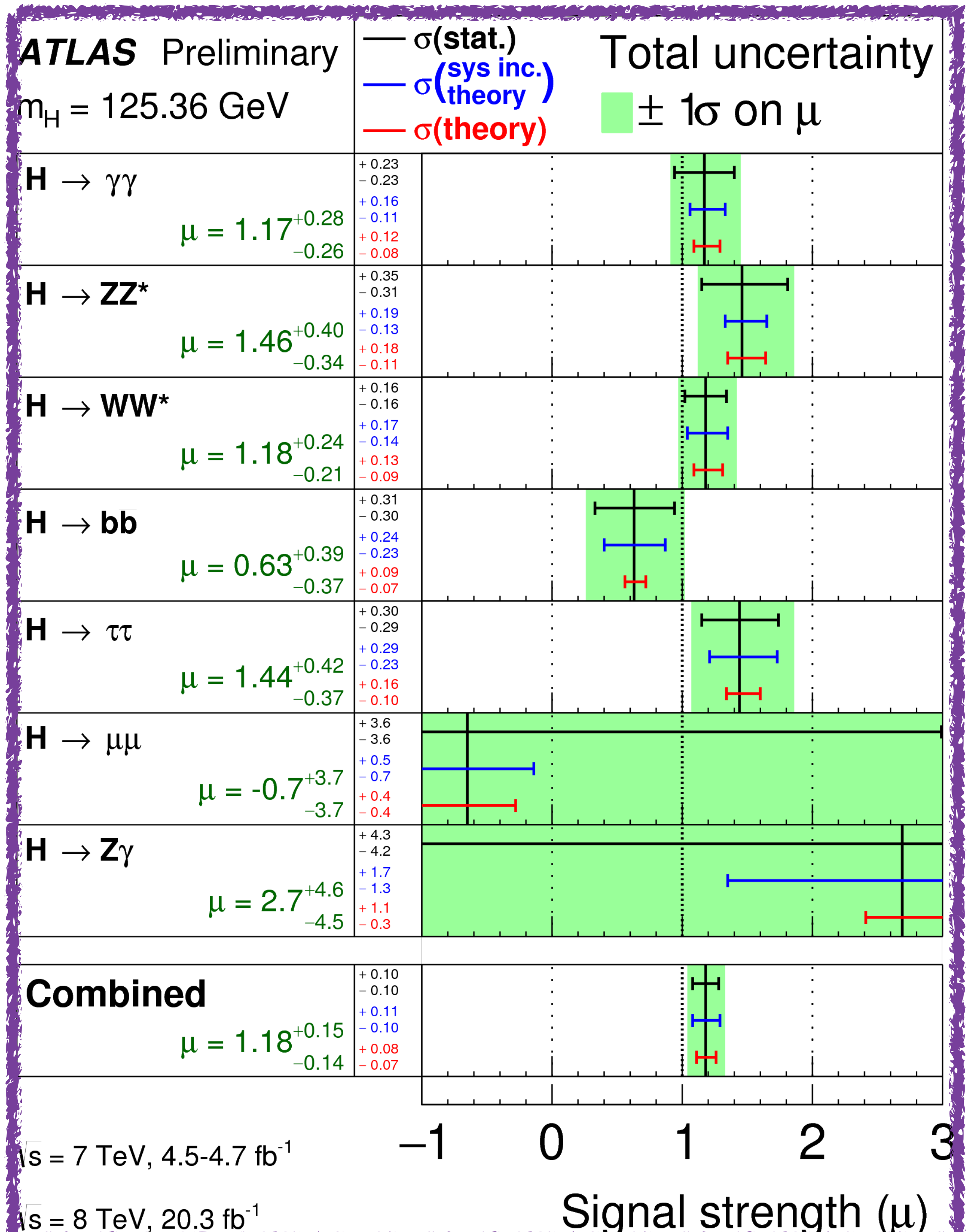
LHC Run 1 & Theory

ATLAS



For all three Higgs 'precision' channels, theory uncertainty is the dominant source of systematic uncertainty !

LHC Run II Prospects



- The dominant component of the systematic error on the signal strength is theory (~10-15%).
- The statistical error from LHC Run I is the largest (~20%), this however will improve during LHC Run II.

Run II prospects:

x2.5 increase in cross section

x15 increase in luminosity (300 fb^{-1})

~ 40 times more events

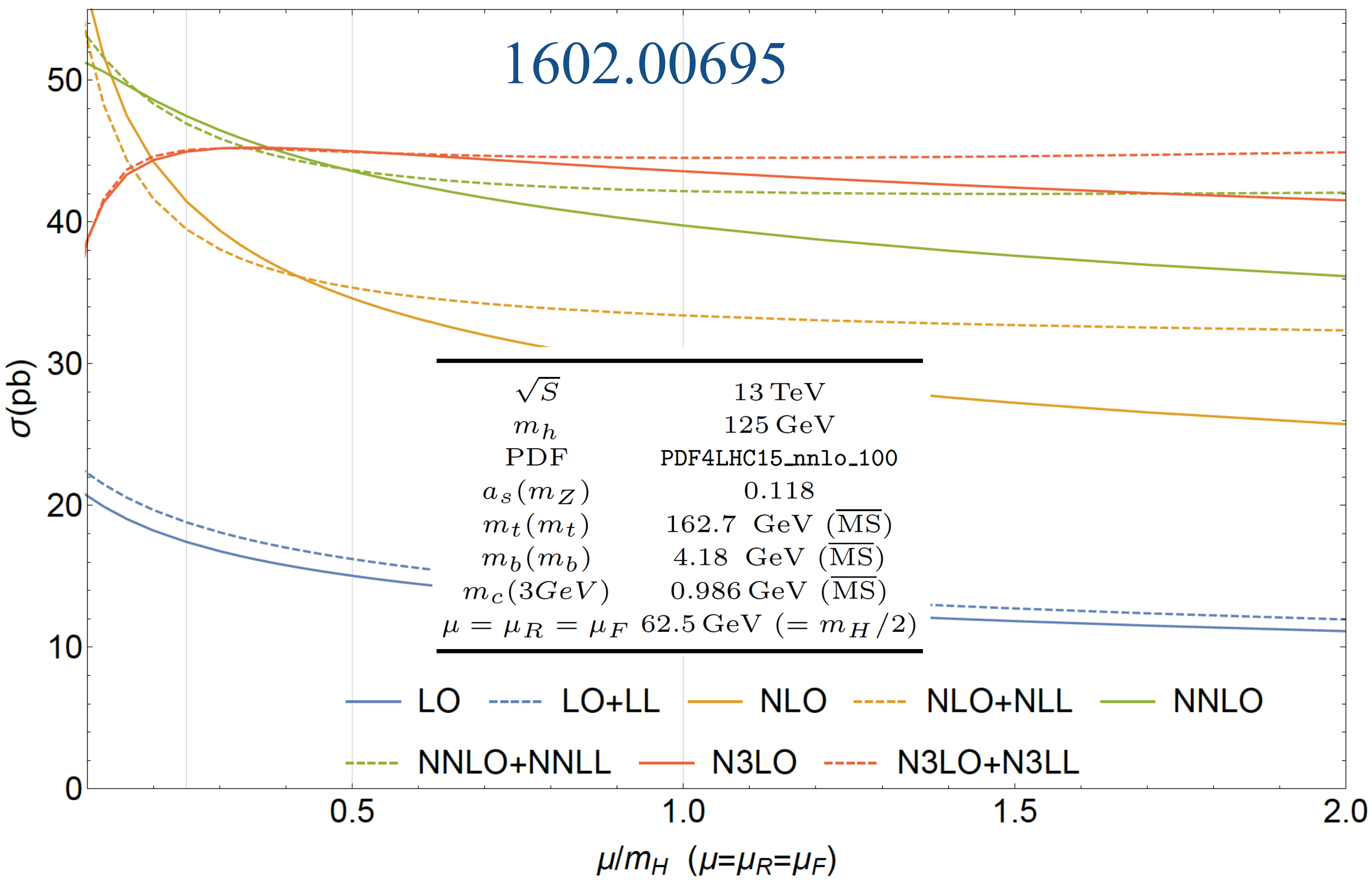
Stat. error in 3-4% range

Theory error becoming a limiting factor in interpreting Run II data.

Inclusive Cross Sections

Higgs Production @ N^3LO in Gluon Fusion

- Remarkable recent progress: the inclusive cross section for Higgs production in gluon fusion is now known at N^3LO in QCD.
  (Anastasiou, Duhr, Dulat, Furlan, Gehrmann, Herzog, Lazopoulos, Mistlberger, 2016)



- Important input for Higgs couplings analysis
- Much smaller scale dependence at N^3LO: ~**1.9% vs 9% @ NNLO** for $\mu \in [m_H/4, m_H]$
- Perturbative expansion stabilized at N^3LO: **~ +3%** shift from NNLO
- Impact of threshold resummation is invisible for $\mu = m_H/2$

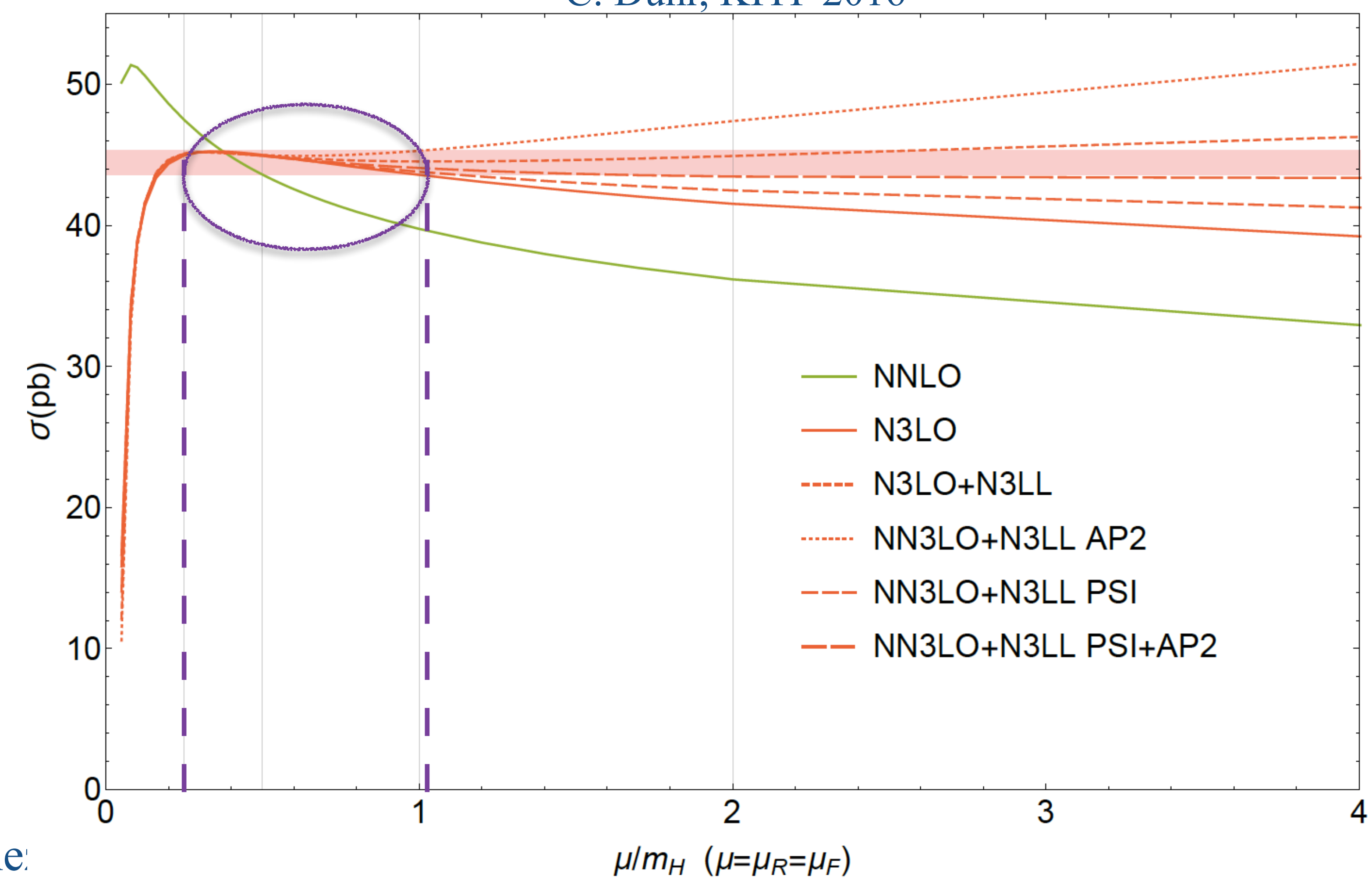
Higgs Production @ N^3LO in Gluon Fusion

13 TeV

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

- Should we worry about missing higher order corrections beyond N^3LO? A possible way of estimating them is to look at the dominant soft-gluon contributions around the threshold, which are resummable to all orders.

C. Duhr, KITP 2016



- Different resummation schemes show that missing higher order corrections are included in the N^3LO error band for $\mu \in [m_H/4, m_H]$.

Higgs Production @ N^{3}LO in Gluon Fusion

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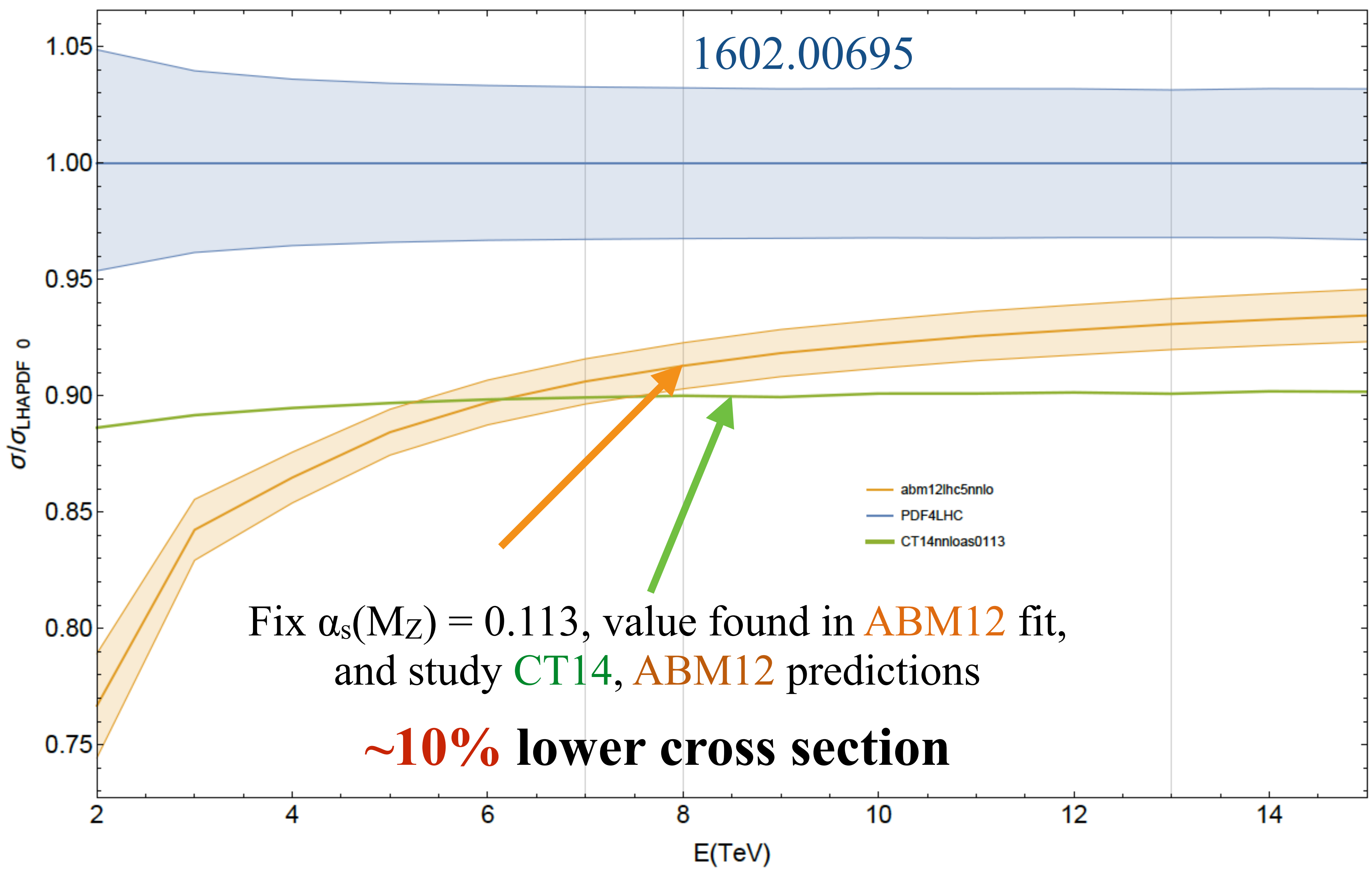
- The result includes various effects besides N^{3}LO QCD corrections in the heavy top mass limit, rescaled by $\frac{\sigma^{\mathbf{LO}}_{\mathbf{excat}}}{\sigma^{\mathbf{LO}}_{\mathbf{EFT}}}$, and accounts for various sources of uncertainties:

  - m_t and m_b mass effects are included exactly at NLO.
  - NNLO top mass effects accounted for in the $1/m_t$ limit (Harlander, Mantler, Marzani, Ozeren, 2009).
  - Exact NLO EW corrections (Actis, Passarino, Sturm, Uccirati, 2008).
  - Mixed QCD-EW effects in an EFT approach (Anastasiou, R.B., Petriello, 2008).
  - The theory error accounts for an estimate of the missing N^{3}LO PDFs and the truncation error associated with the calculation approach at N^{3}LO.
  - PDF and α_s errors combined quadratically.

Higgs Production @ N^{3}LO in Gluon Fusion

- The N^{3}LO result assumes PDF4LHC $\alpha_s(M_Z)$ recommendation: 0.1180±0.0015
- There is a strong parametric dependence of ggH cross section on α_s: LO~α_s^2
- DIS and some e+e- fits prefer lower value of $\alpha_s(M_Z)$



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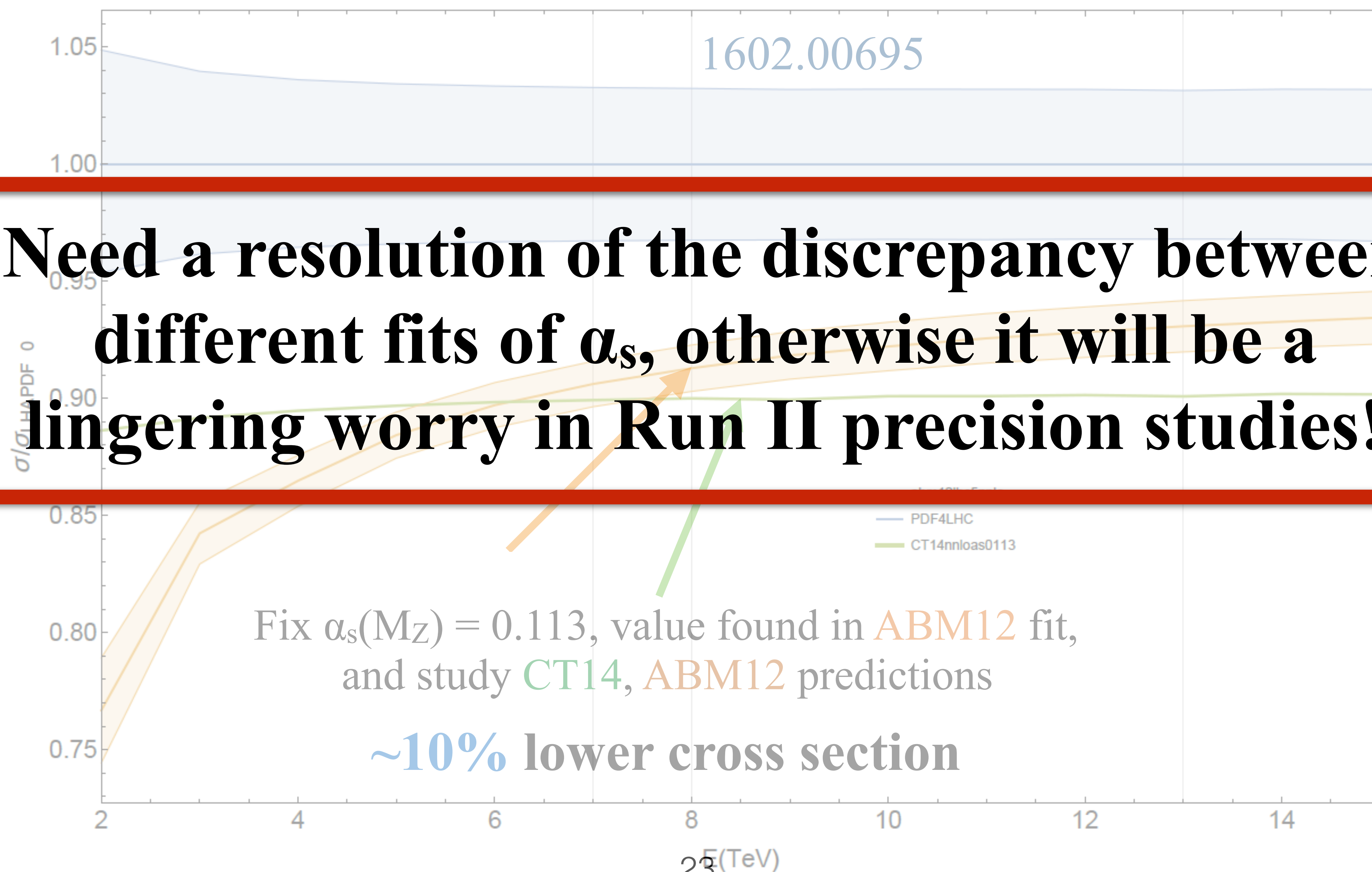
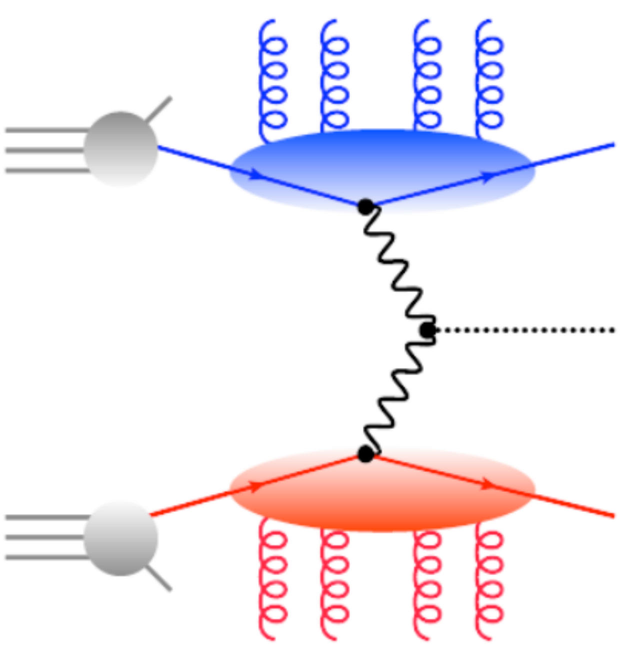


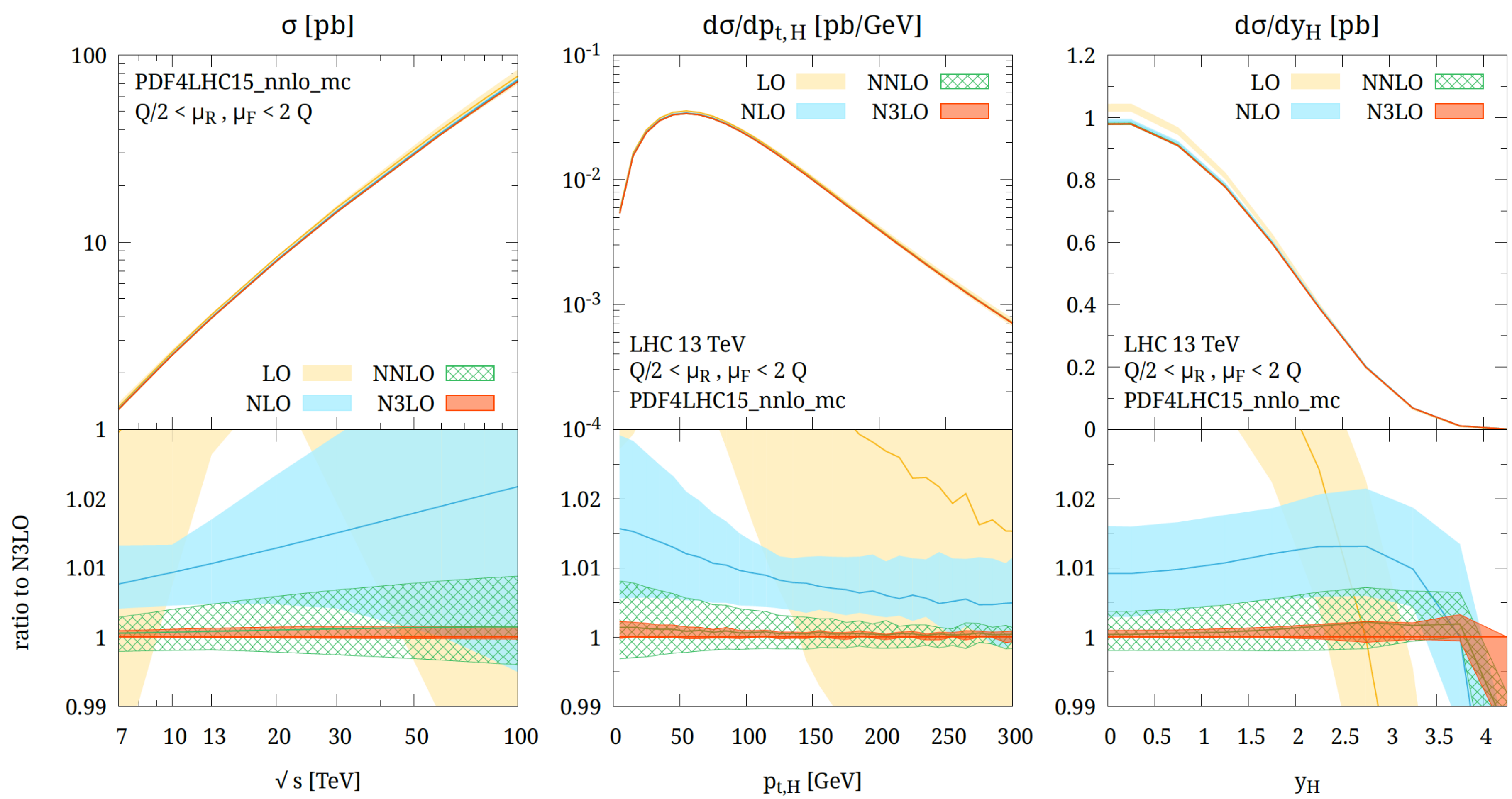
Need a resolution of the discrepancy between different fits of α_s, otherwise it will be a lingering worry in Run II precision studies!

Inclusive Higgs Production in VBF

- Calculated first at NNLO in QCD in the structure function approach. Small correction ~1% and uncertainty ~1-2% (Bolzoni, Maltoni, Moch, Zaro, 2011)
- Now also known at N^3LO in QCD. Correction tiny, 0.1-0.2% and the uncertainty is lower than 0.2% (Dreyer, Karlsberg, 2016)
- Can help perform accurate Higgs couplings measurements.

(Dreyer, Karlsberg, 2016)





Exclusive Higgs Cross Section

Why go exclusive?

- Kinematic distributions are used to extract or constrain particles properties such as their couplings.
- How different can the differential distributions be from the inclusive case? take VBF as an example:

13TeV, anti-KT, R=0.4, NNPDF

	$\sigma^{(\text{no cuts})}$ [pb]	$\sigma^{(\text{VBF cuts})}$ [pb]
LO	$4.032^{+0.057}_{-0.069}$	$0.957^{+0.066}_{-0.059}$
NLO	$3.929^{+0.024}_{-0.023}$	$0.876^{+0.008}_{-0.018}$
NNLO	$3.888^{+0.016}_{-0.012}$	$0.826^{+0.013}_{-0.014}$
	~ -1%	~ -5%

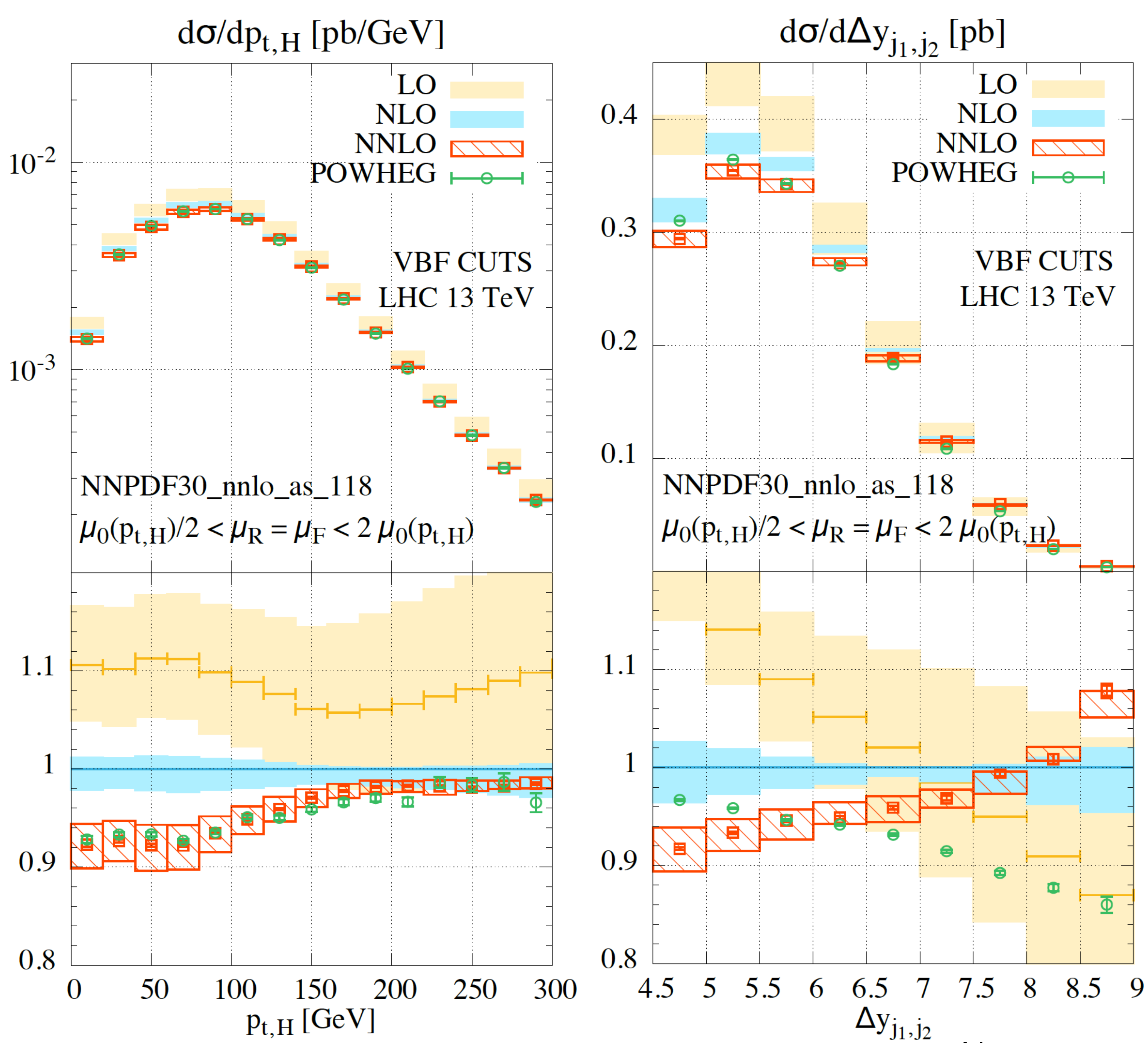
Cacciari, Dreyer, Karlberg, Salam, Zanderighi 2015

- The NNLO corrections for the cross section with VBF cuts are 5 times larger than the inclusive case, and large enough to influence precision studies.

Differential VBF@NNLO

- Can now study kinematic observables with realistic cuts

1506.02660

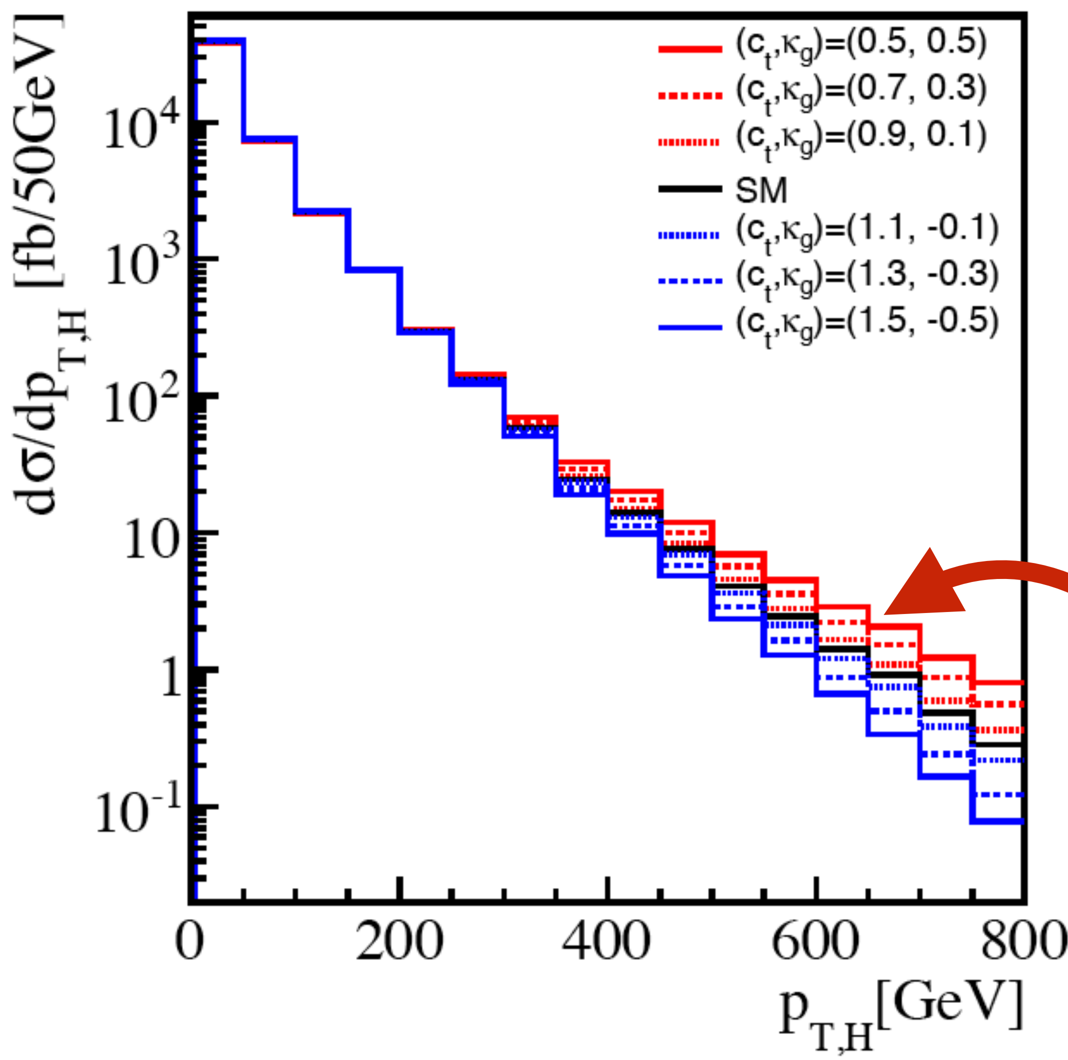


- Non trivial Kinematic dependence of the K-factors.
- NNLO Corrections can be as large as 10% for some distributions.
- NLO+parton shower agrees well with NNLO for P_{TH} but not for $\Delta y_{j1,j2}$.
- Recently NNLO QCD and NLO EW corrections were merged within the HXSWG activities.

The Higgs P_T spectrum

- The Higgs transverse momentum is an important observable that probes Higgs properties. It can be used to disentangle the ggH and its possible BSM contributions from ttH couplings for example:

1405.4295



Schlaffer, Spannowsky, Takeuchi, Weiler, Wymant

$$\mathcal{L}_{eff} = -c_t \frac{m_t}{v} t\bar{t}H + k_g \frac{\alpha_s}{12\,\pi} \frac{h}{v} G^a_{\mu\nu} G^{a\,\mu\nu} + \mathcal{L}_{QCD}$$

$$\frac{\sigma(c_t, \kappa_g)}{\sigma_{\rm SM}} \approx (c_t + \kappa_g)^2$$

Inclusive production cannot distinguish BSM scenarios from SM one!

Important to calculate p_{TH} precisely!

Higgs+jet @ NNLO in QCD

- An accurate understanding of this cross section helps improve the signal significance when jet binning is used.
- Need improvement on two fronts:

$O(\alpha_S^2)$ correction in the $m_t \rightarrow \infty$ limit

↓

Three independent NNLO results are now available for this process

↓

R.B., Caola, Melnikov, Petriello, Schulze, 2015

R.B., Focke, Giele, Liu, Petriello, 2015

Chen, Gehrmann, Glover, Jacquier, 2016

$O(\alpha_S)$ corrections to $1/m_t$ suppressed operators

↓

Approximate results incorporating finite m_t effects show that deviations from $m_t \rightarrow \infty$ start at $p_{TH} > 150$GeV

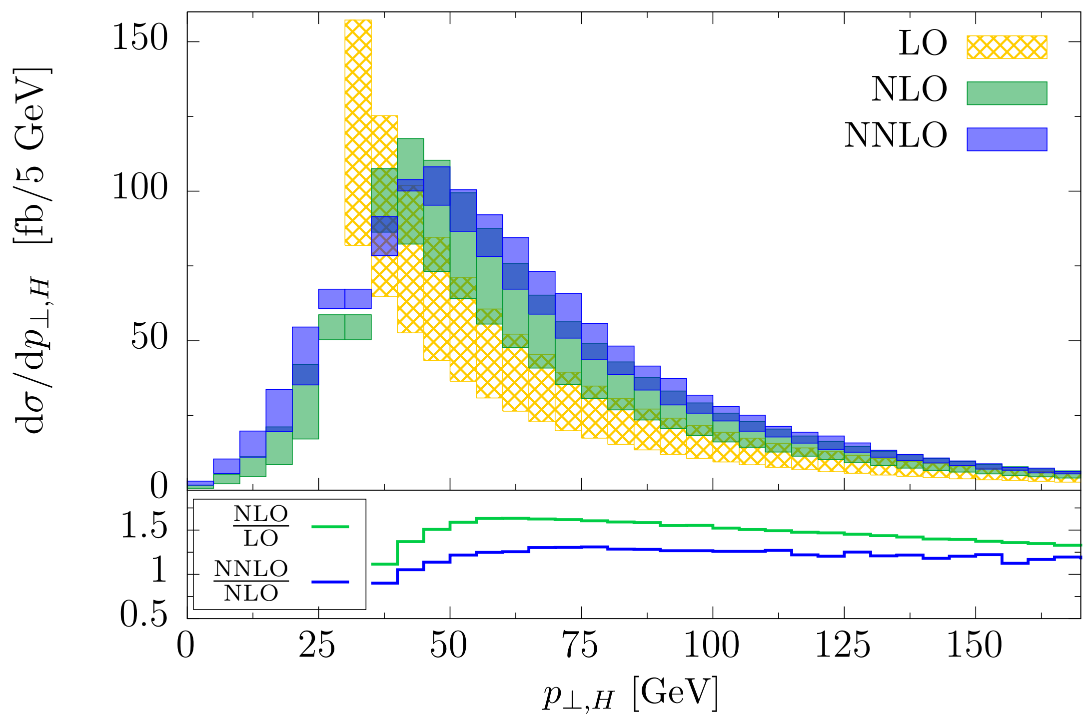
↓

Harlander, Neumann, Ozeren, 2012

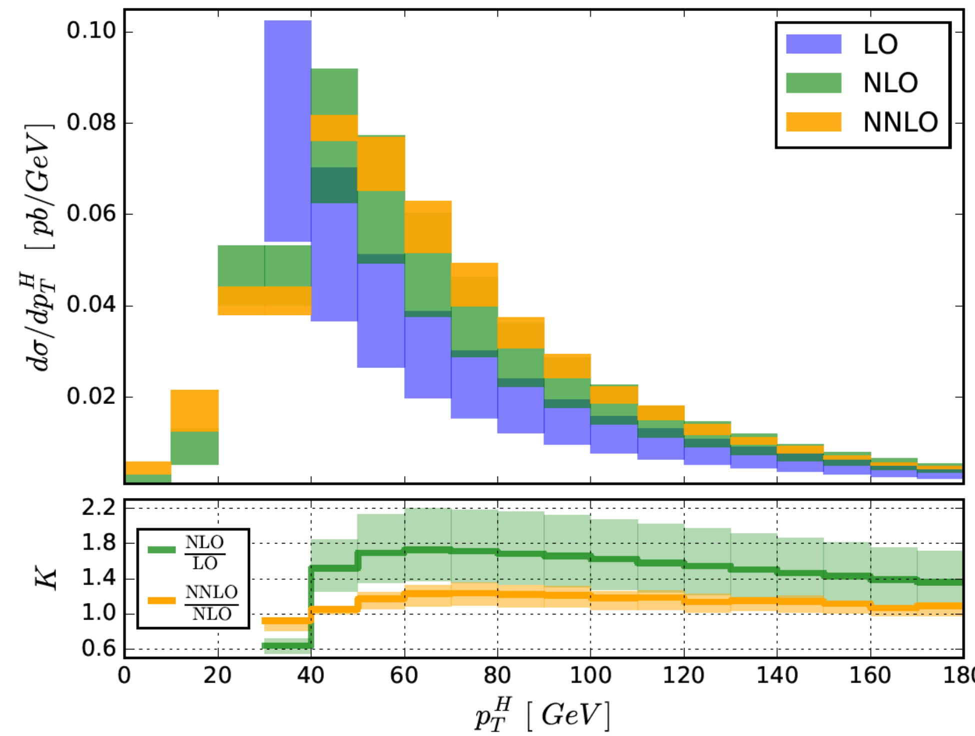
Dawson, Lewis, Zeng, 2014

- H+j@NLO with exact m_t dependence still missing

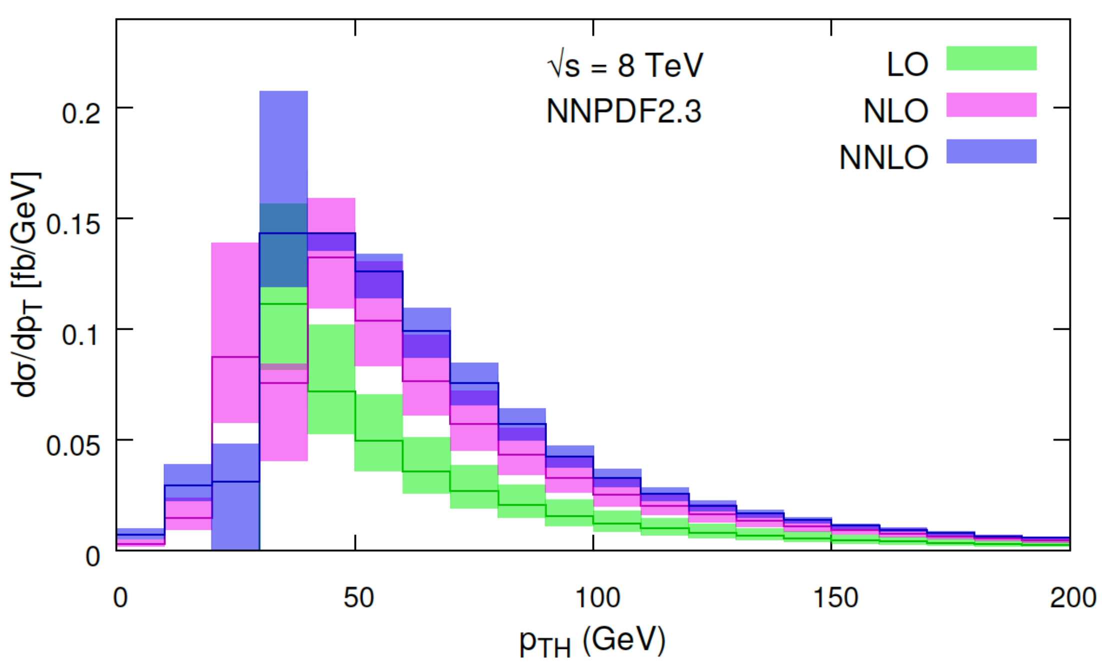
Higgs+jet @ NNLO in QCD



R.B, Caola, Melnikov, Petriello, Schulze, 2015



R.B, Focke, Giele, Liu ,Petriello, 2015



Chen, Gehrmann, Glover, Jacquier, 2016

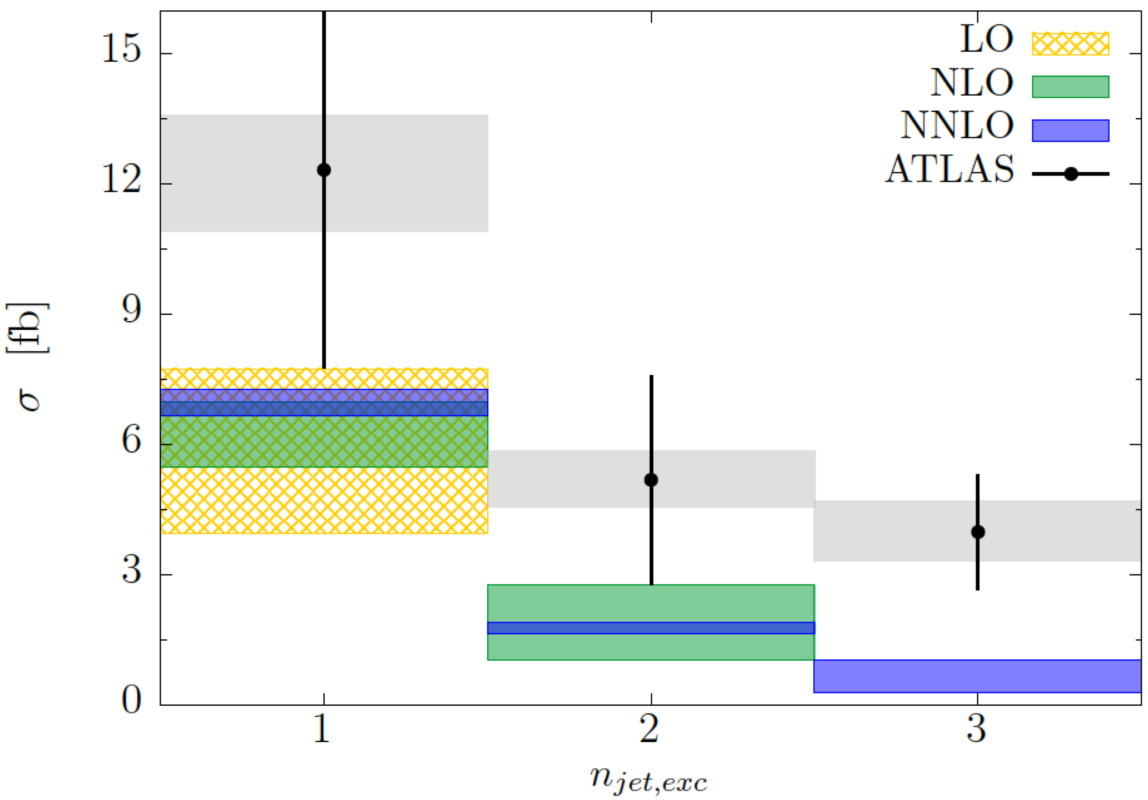
- Good perturbative behavior and smaller uncertainties for all differential distributions (p_{TH}, p_{Tj}, Y_j)
- Corrections in fiducial σ are roughly 20% for $\mu = m_H$ and 4% for for $\mu = m_H/2$.

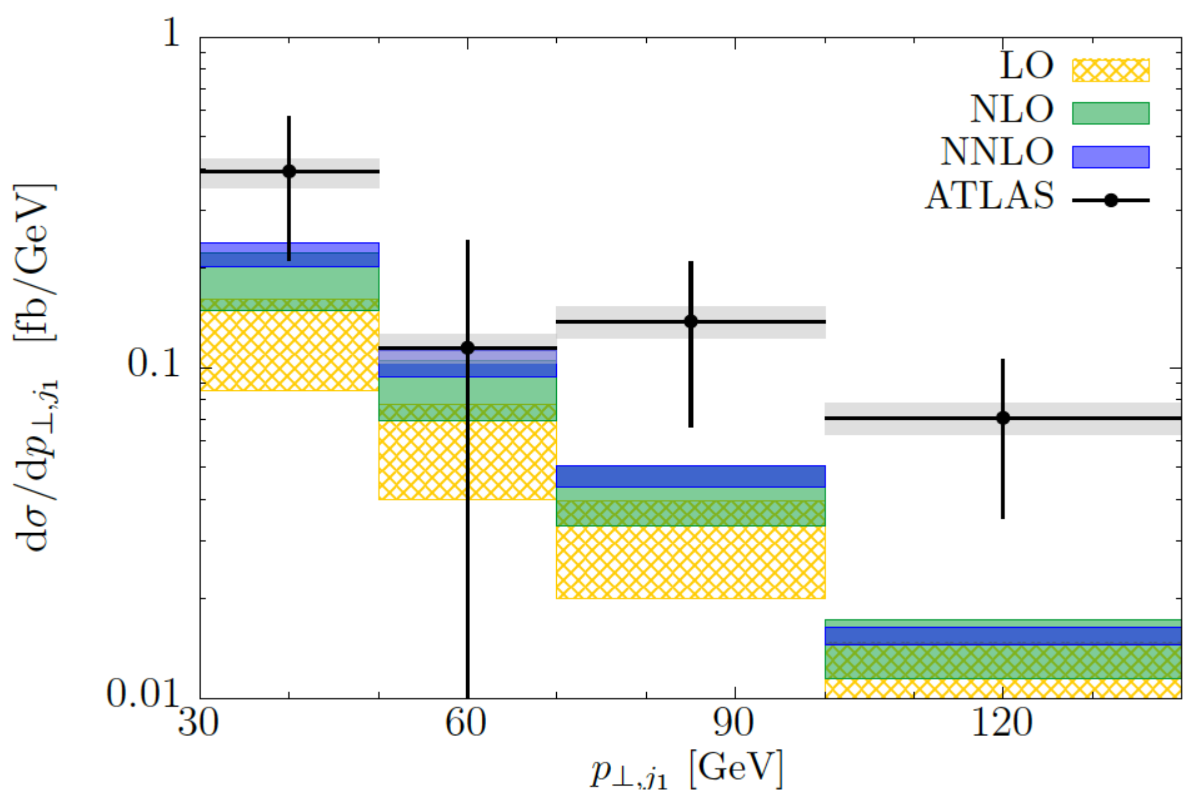
Higgs+jet @ NNLO in QCD

- Including the decay of Higgs to photons:

Caola, Melnikov, Schulze 2015; Chen, Cruz-Martinez, Gehrmann, Glover, Jacquier, 2016

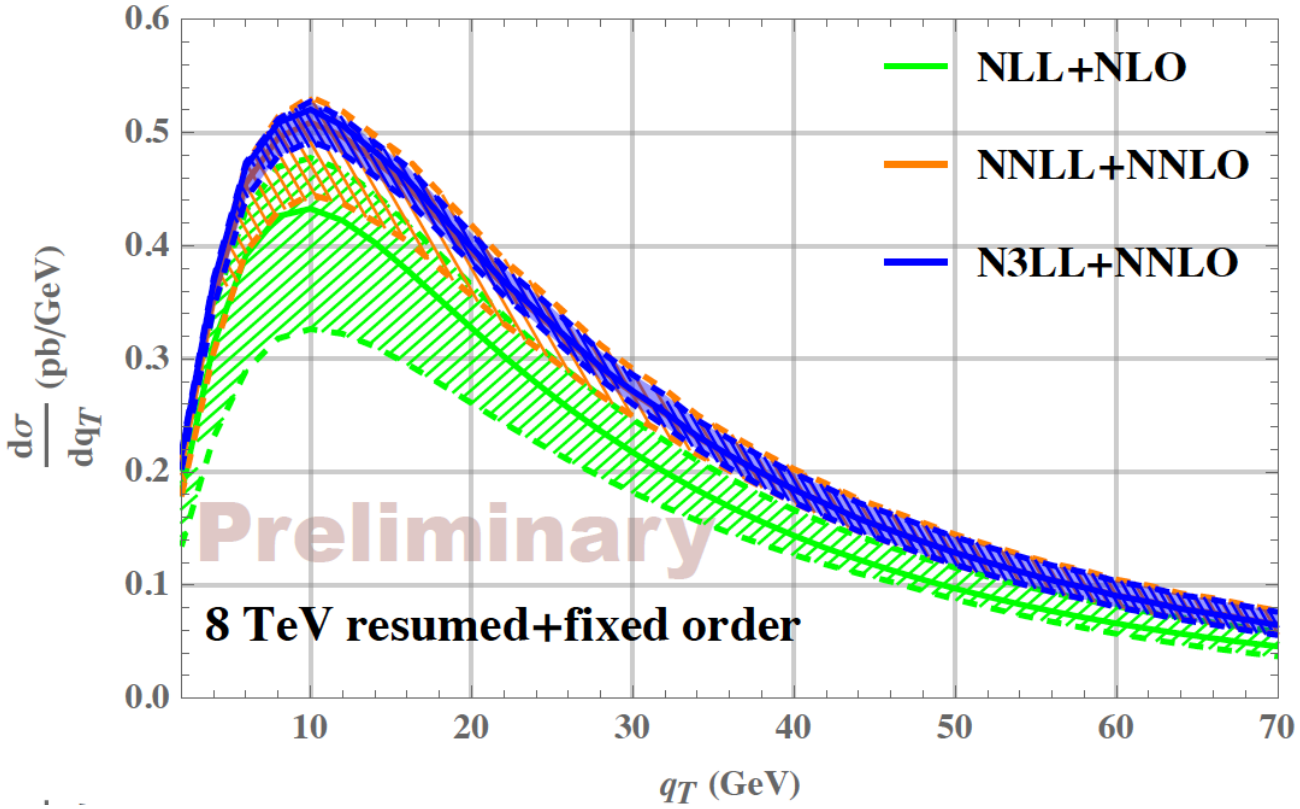
Initial indications show harder p_{Tj} spectrum and more jets than predicted by theory, although data uncertainties are large. Awaiting more precise Run II data!





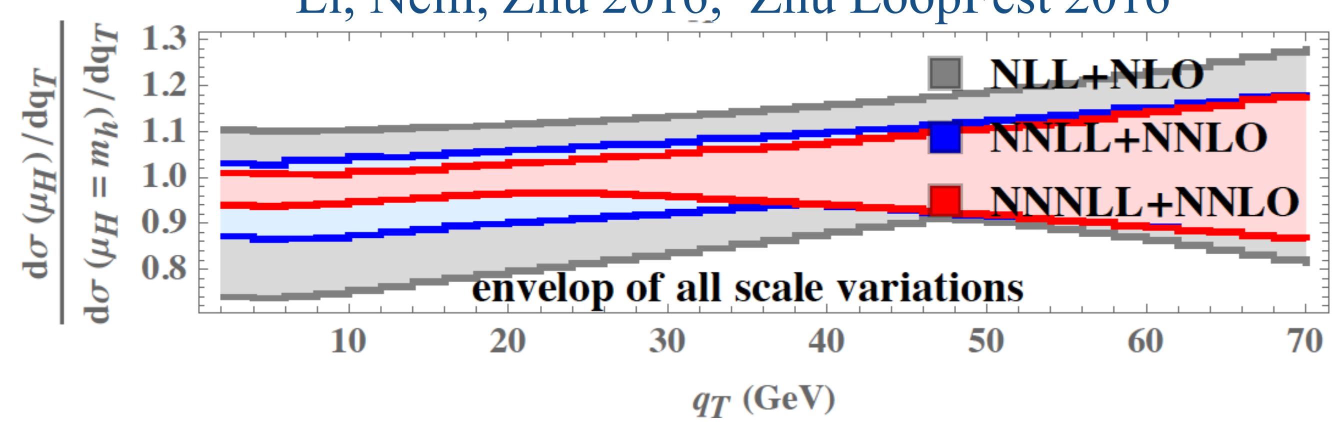
Caola, Melnikov, Schulze, 2015

The Higgs P_T resummation



- New calculation of N^3LL anomalous dimension needed for Higgs low p_T resummation

Li, Neill, Zhu 2016; Zhu LoopFest 2016



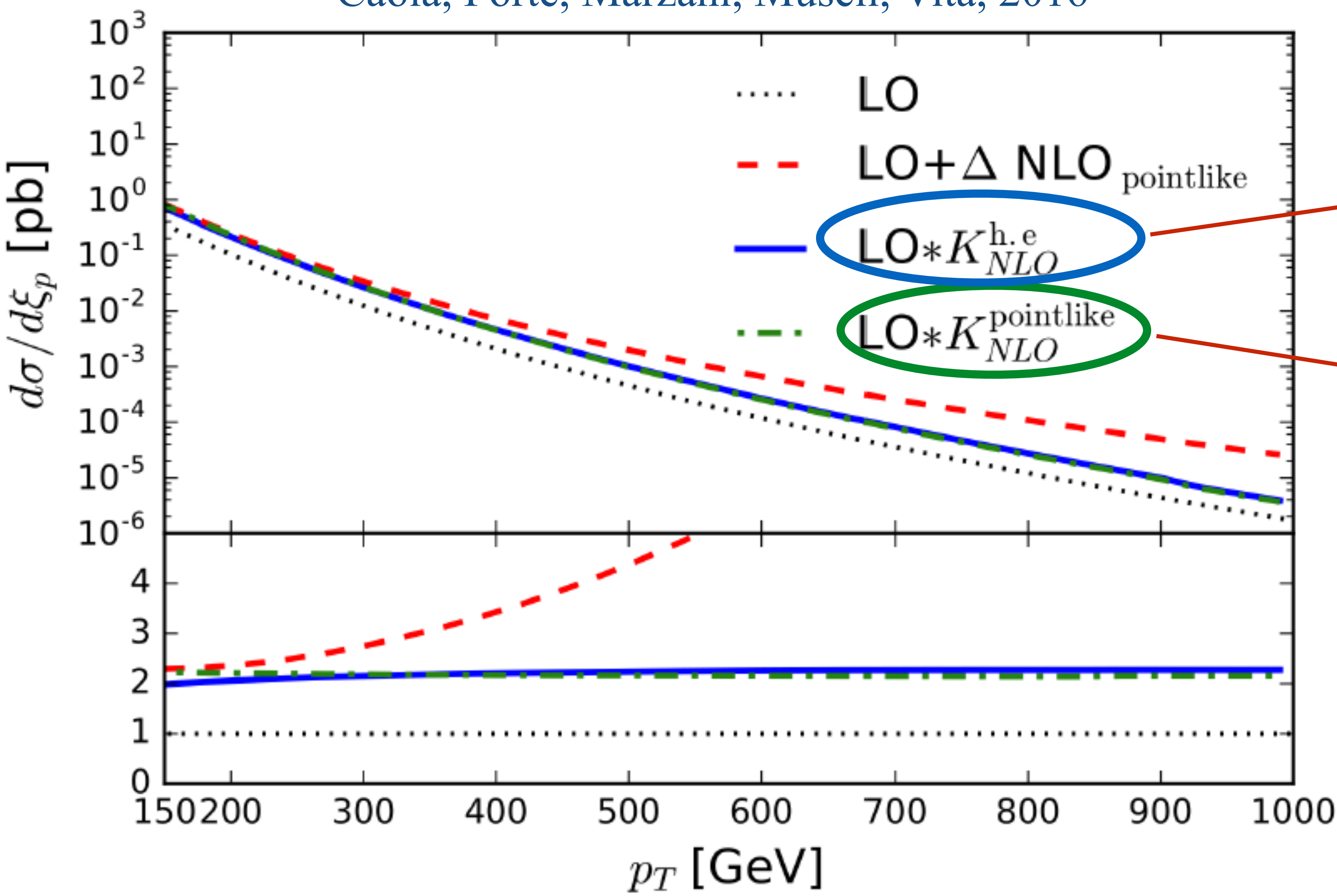
$$\ln \sigma(b) \sim - \int_{1/b^2}^{m_H^2} \frac{d\bar{\mu}^2}{\bar{\mu}^2} \left[\ln\left(\frac{m_H^2}{\bar{\mu}^2}\right) A[\alpha_s(\bar{\mu})] + B[\alpha_s(\bar{\mu})] \right]$$

LL	NLL	NNLL	N3LL
A_1	A_2	A_3	A_4
	B_1	B_2	B_3 (New)

What was known before: LL, NLL, NNLL

Finite Mass effects for Higgs P_T

Caola, Forte, Marzani, Museli, Vita, 2016



Uses high-energy limit:
exact LO × high-energy K-factor

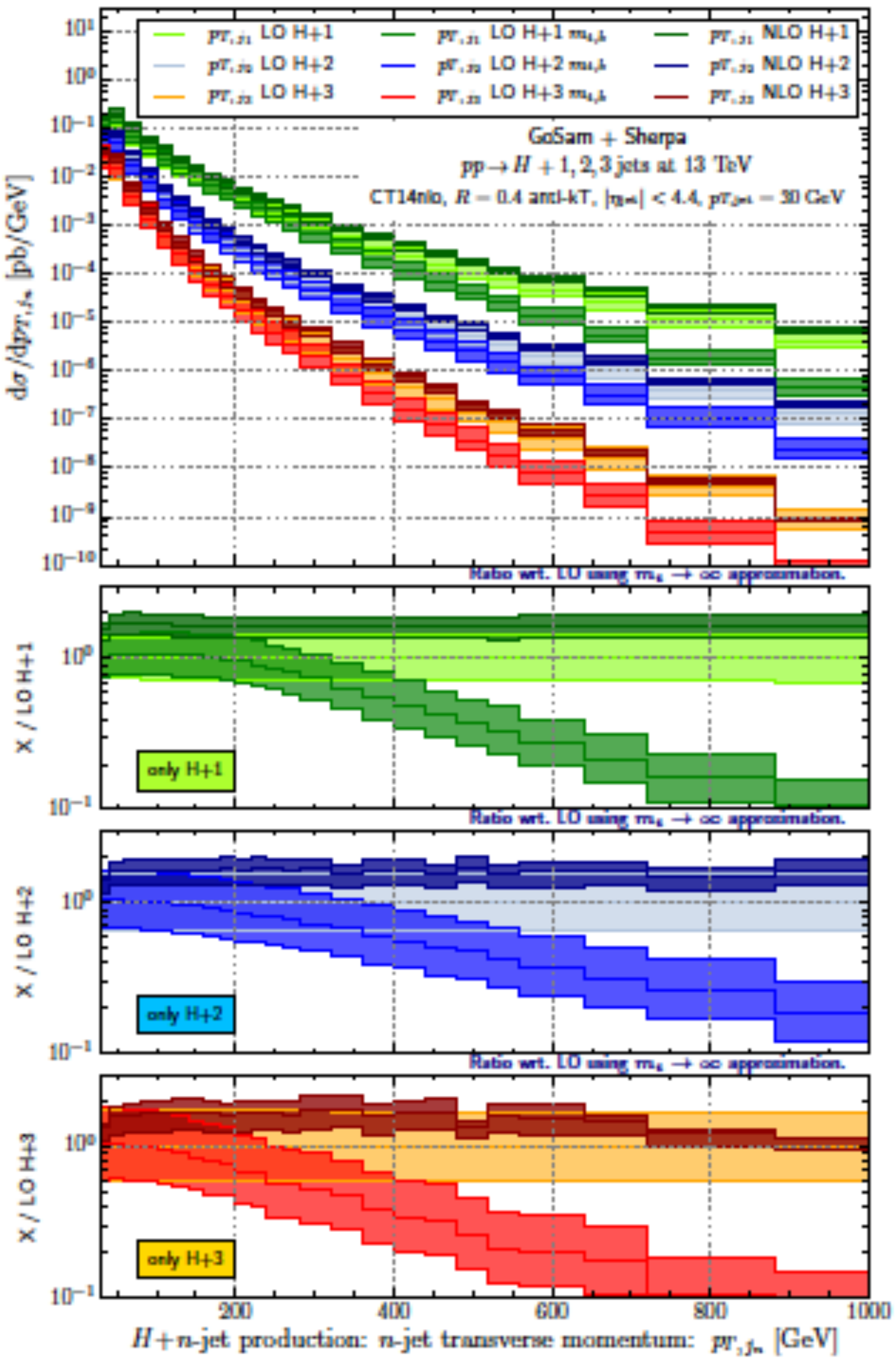
Usual way of accounting for finite mass effects:
exact LO × EFT K-factor

High-energy K-factor calculated using BFKL approach

- Interesting agreement between two different approaches to model high-P_T Higgs production. Would be nice to confirm with an exact NLO calculation.

Finite Mass effects for Higgs Production

1608.01195



- Also important to have finite mass effects for other kinematic distributions for Higgs production with multiple jets

  Greiner, Hoeche, Luisoni, Schoenherr, Winter 2016

- New understanding of bottom-quark Higgs effects on Higgs p_T

  Melnikov, Penin 2016

Hadronic cross section (abelian terms only)

$$\frac{d\sigma_{pp\to H+j}}{dp_\perp^2} = \frac{d\sigma^{(0)}_{pp\to H+j}}{dp_\perp^2}\left\{1 - \frac{3m_b^2}{m_H^2}L^2\left[1 - \frac{x}{12}\left(1-\tau^3+\tau^4\right) + \frac{x^2}{48}\left(\frac{4}{15} - \tau^3 + 2\tau^4 - \frac{7\tau^5}{5} + \frac{2\tau^6}{5}\right) + \mathcal{O}(x^3)\right] + \mathcal{O}(m_b^4)\right\}$$

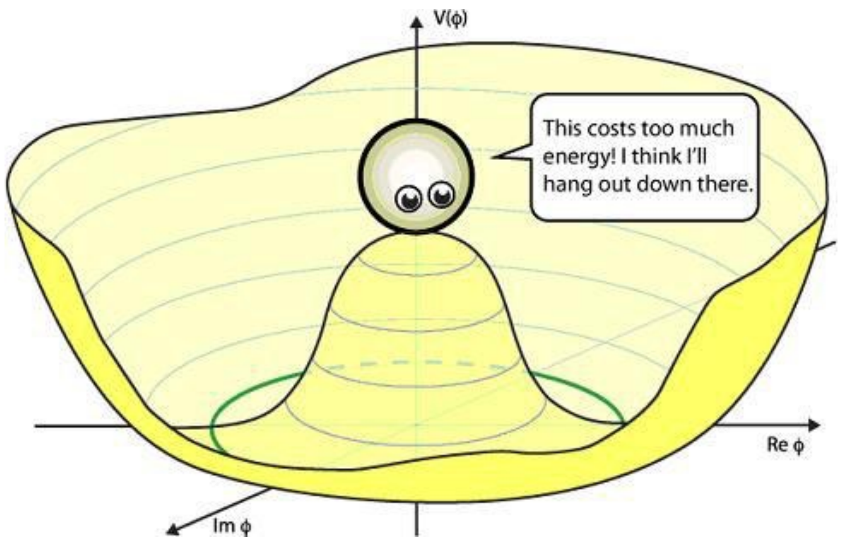
$$\tau = \ln(m_b^2/p_\perp^2)/L, \qquad \zeta = \ln(u/t)/L, \qquad x = \frac{C_F\alpha_s}{2\pi}L^2$$

$$L = \ln(m_b^2/s), \qquad 0 < \tau, |\zeta| < 1, \qquad x \sim 1$$

Di-Higgs Production

- The Higgs that we know so far is consistent with the SM in its couplings to the observed modes (within 15-40% uncertainty), its mass is known to 0.2% precision, and its spin and parity have good experimental handles. What about the Higgs self coupling?

$$V = \frac{1}{2} m_H^2 H^2 + \lambda_3 v H^3 + \frac{\lambda_4}{4} H^4$$

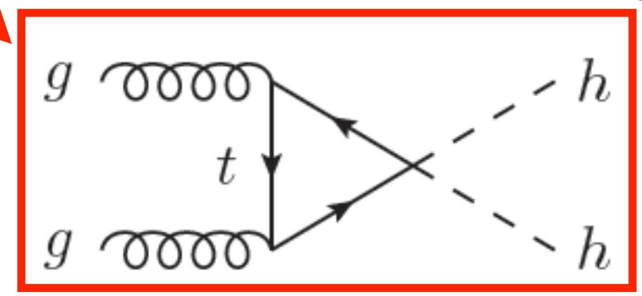


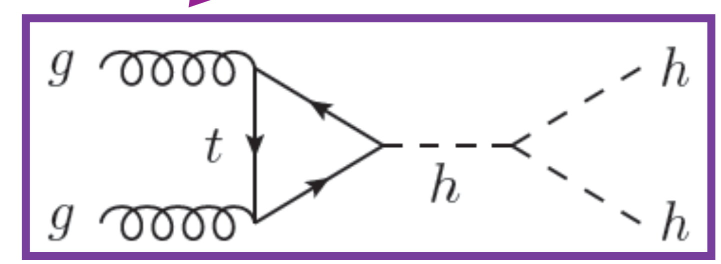
- In the SM the Higgs potential is completely predicted in terms of m_H. Not necessarily true in BSM theories. Need to measure triple and quartic Higgs couplings to check.
- A measurement of di-Higgs production would give a handle on λ_3, any deviation from the SM value could indicate new physics effects.

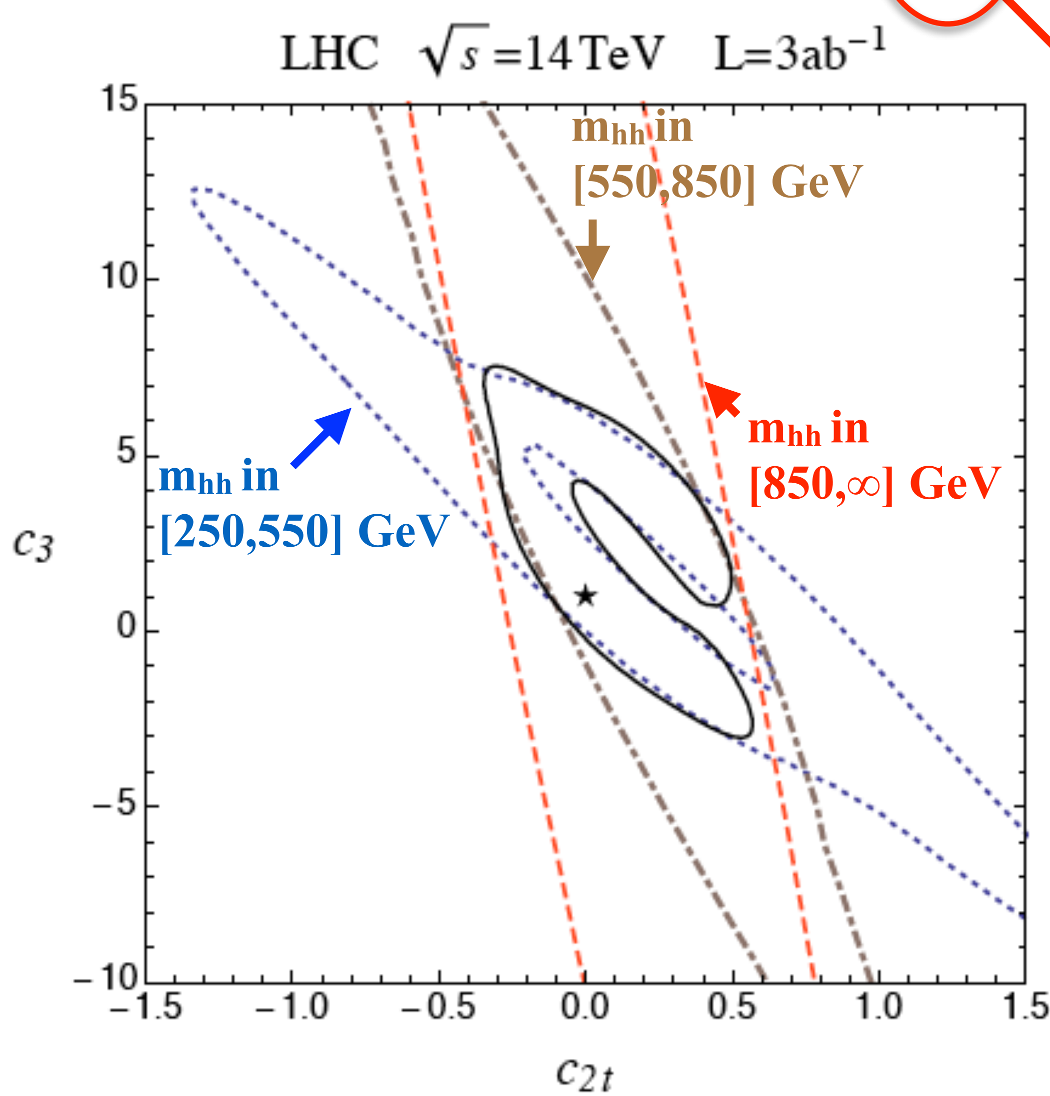
Di-Higgs Production

- An example of a detailed EFT analysis of HH production from 1502.00539:

$$\mathcal{L}_{non-lin} \supset -m_t \bar{t}t \left(c_t \frac{h}{v} + c_{2t}\frac{h^2}{v^2}\right) - c_3 \frac{m_h^2}{2v} h^3 + \frac{g_s^2}{4\pi^2}\left(c_g \frac{h}{v} + c_{2g}\frac{h^2}{2v^2}\right) G^a_{\mu\nu} G^{a\,\mu\nu}$$





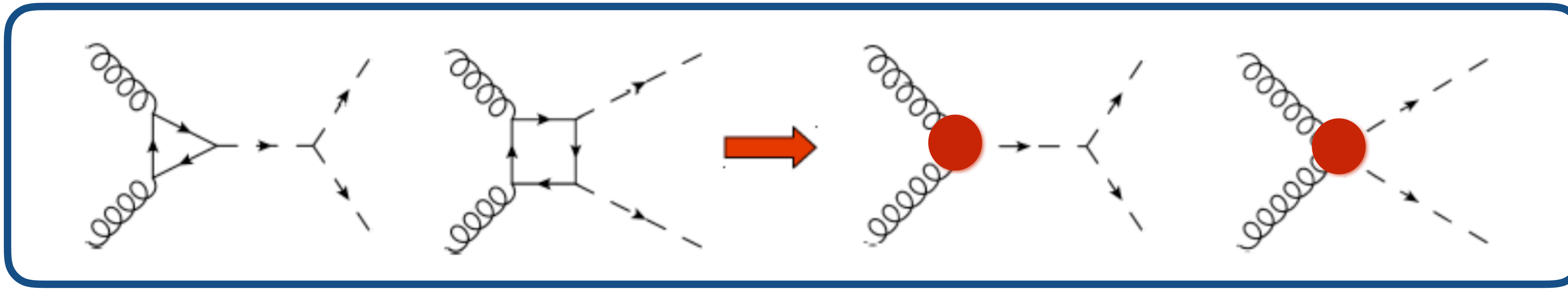


Azatov, Contino, Panico, Son 1502.00539

- Critical to use m_{hh} to break degeneracies between couplings. First higher-order QCD corrections were in heavy-m_t approximation

Di-Higgs Production in EFT

- The leading order diagrams are already one-loop. Use EFT approach to get higher order corrections (normalized to the exact Born similar to single Higgs).



- Several results were obtained in the infinite top mass limit and its extension:
  - LO cross section Plehn et al, 96; Glover, van der Bij '88
  - NLO cross section in EFT Dawson, Dittmaier, Spira, '98
  - NNLO cross section in EFT De Florian, Mazzitelli '13; Grigo et al '14
  - Expansion in 1/mt @ NLO and NNLO Grigo et al '13-'15; Maltoni et al '14
  - Exact mass dependence at NLO real radiation and matching to a parton shower Frederix et al '14; Maltoni et al '14
  - Resumation of threshold logs De Florian, Mazzitelli '15

Di-Higgs Production in EFT

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Question: How reliable are these approximations, especially in the era of precision Higgs studies?

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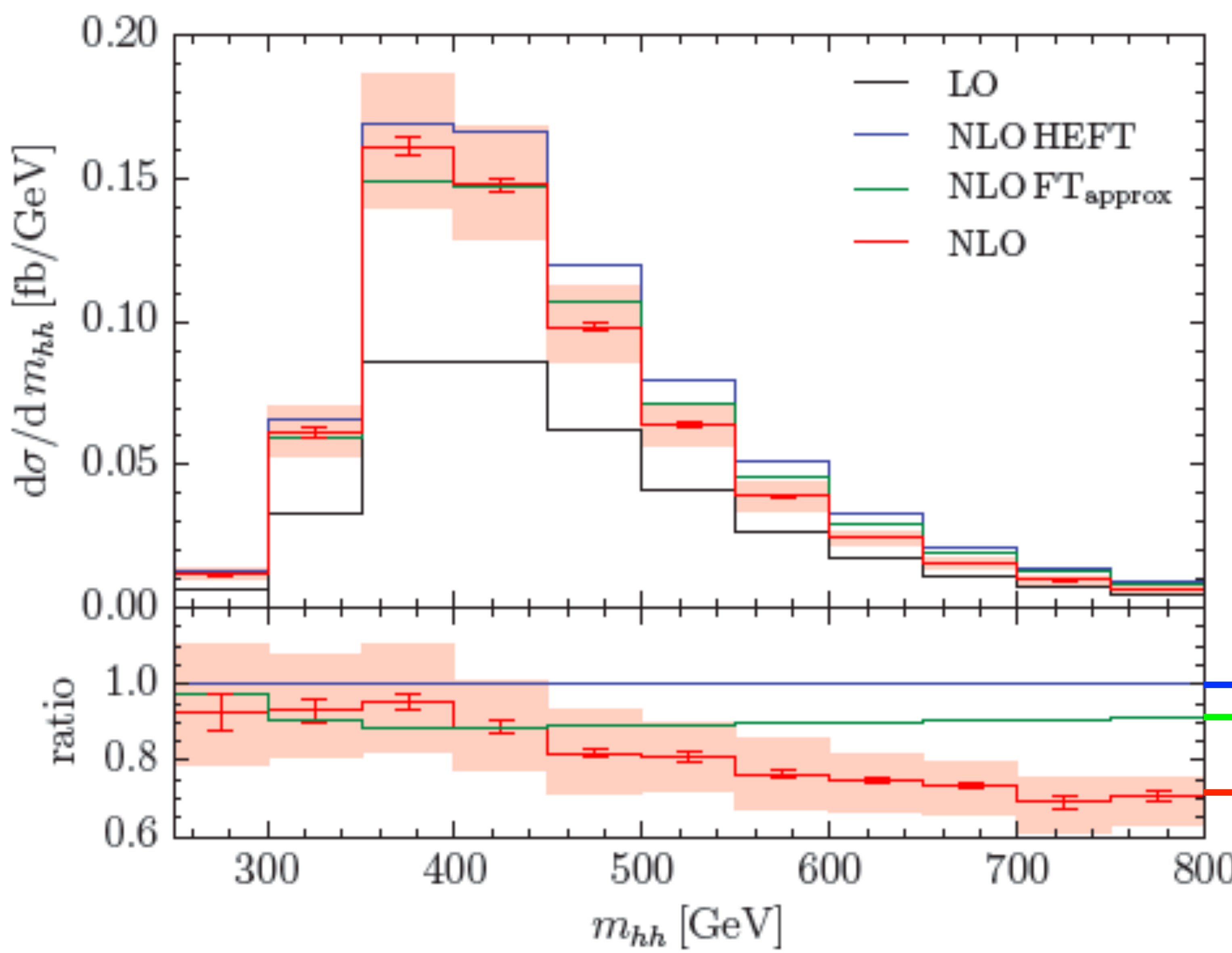
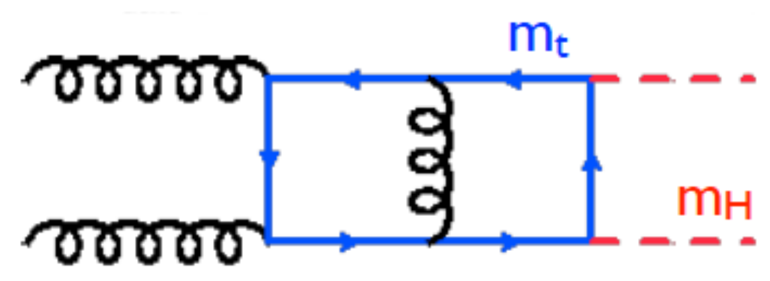
Di-Higgs Production @ NLO with full m_t dependence

- **Large corrections not captured by heavy-m_t approximation!**
  In particular, a strong dependence of the NLO corrections on m_{hh} is missed in the approximation approach





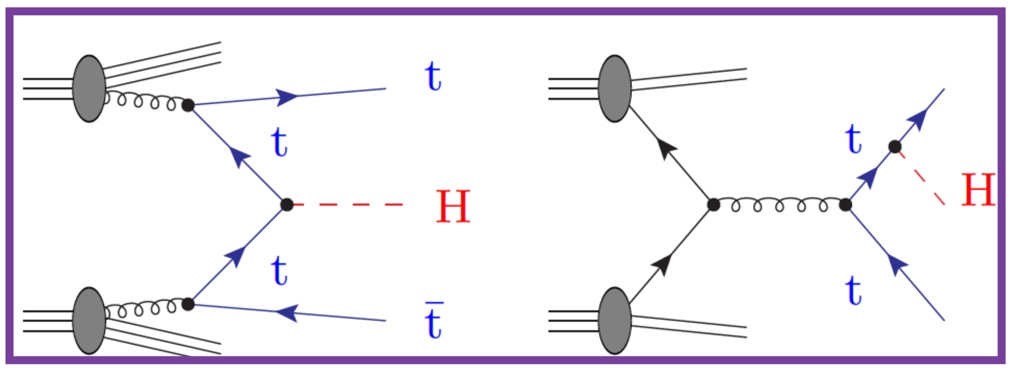
The full higher-order corrections are essential for the interpretation of this measurement!

Heavy-m_t approximation
Exact m_t in real radiation only
Exact NLO result

Borowka, Greiner, Heinrich, Jones, Kerner, Schlenk, Schubert, Zirke 1604.06447

ttH Production

- Allows a probe of the ttH coupling directly at tree level.



J. Keller, ICHEP 2016

Cross section (fb) @NLO	$t\bar{t}H$	$t\bar{t}W$	$t\bar{t}Z$	$t\bar{t}$ (NNLO)
8 TeV	133	232	206	2,53E+05
13 TeV	507	566	760	8,32E+05
13 TeV / 8TeV	3.8	2.4	3.7	3.3

- LHC Run II offers a large increase in the ttH cross section, but backgrounds increase at a comparative rate in the signal region.
- How well are we doing in modeling the signal and backgrounds?

ttH Production

- Large modeling uncertainty for the ttbb mode

J. Keller, ICHEP 2016

Uncertainty source	$\Delta\mu$	
$t\bar{t}+\geq 1b$ modelling	+0.53	−0.53
Jet flavour tagging	+0.26	−0.26
$t\bar{t}H$ modelling	+0.32	−0.20
Background model statistics	+0.25	−0.25
$t\bar{t}+\geq 1c$ modelling	+0.24	−0.23
Jet energy scale and resolution	+0.19	−0.19
$t\bar{t}$+light modelling	+0.19	−0.18
Other background modelling	+0.18	−0.18
Jet-vertex association, pileup modelling	+0.12	−0.12
Luminosity	+0.12	−0.12
$t\bar{t}Z$ modelling	+0.06	−0.06
Light lepton (e, μ) ID, isolation, trigger	+0.05	−0.05
Total systematic uncertainty	+0.90	−0.75
$t\bar{t}+\geq 1b$ normalisation	+0.34	−0.34
$t\bar{t}+\geq 1c$ normalisation	+0.14	−0.14
Statistical uncertainty	+0.49	−0.49
Total uncertainty	+1.02	−0.89

ttH Production

J. Keller, ICHEP 2016

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$t\bar{t}+\geq 1b$ modelling	+0.53	−0.53
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J. Keller, ICHEP 2016

Theory errors for the signal and background are larger than many other uncertainties affecting the signal strength!

ttH Production: Current Status

- NLO corrections to the signal pp → ttH with on shell final-state particles
  - QCD corrections with on shell final-state particles Beenakker et al ’01,’02; Dawson et al ’01-’03
  - Parton-shower matching Frederix et al ’11; Garzelli et al ’11
  - EW corrections with on shell final-state particles Frixione et al ’14, ’15 (stable top/Higgs); Zhang et al ’14 (NWA)
  - QCD corrections with off shell tops Denner et al ’15
- NLO corrections to the dominant background process pp → ttbb
  - QCD corrections Bredenstein et al ’08-’10; Bevilacqua et al ’09
  - Parton-shower matching Kardos et al ’13
  - QCD corrections for massive bottom quarks and parton-shower matching Cascioli et al ’13
  - QCD corrections with off shell final-state particles Denner et al ’15
- NLO corrections to the ttjj background
  - QCD corrections Bevilacqua et al ’10
  - Parton-shower matching Hoeche et al ’14

ttH(→bb) in the Boosted Region

- Matching the fixed order NLO result to a parton shower for ttbb showed a significant difference in the cross section compared to pure NLO in the Higgs-signal region.

Cascioli, Maierhoefer, Moretti, Pozzorini, Siegert, 2013

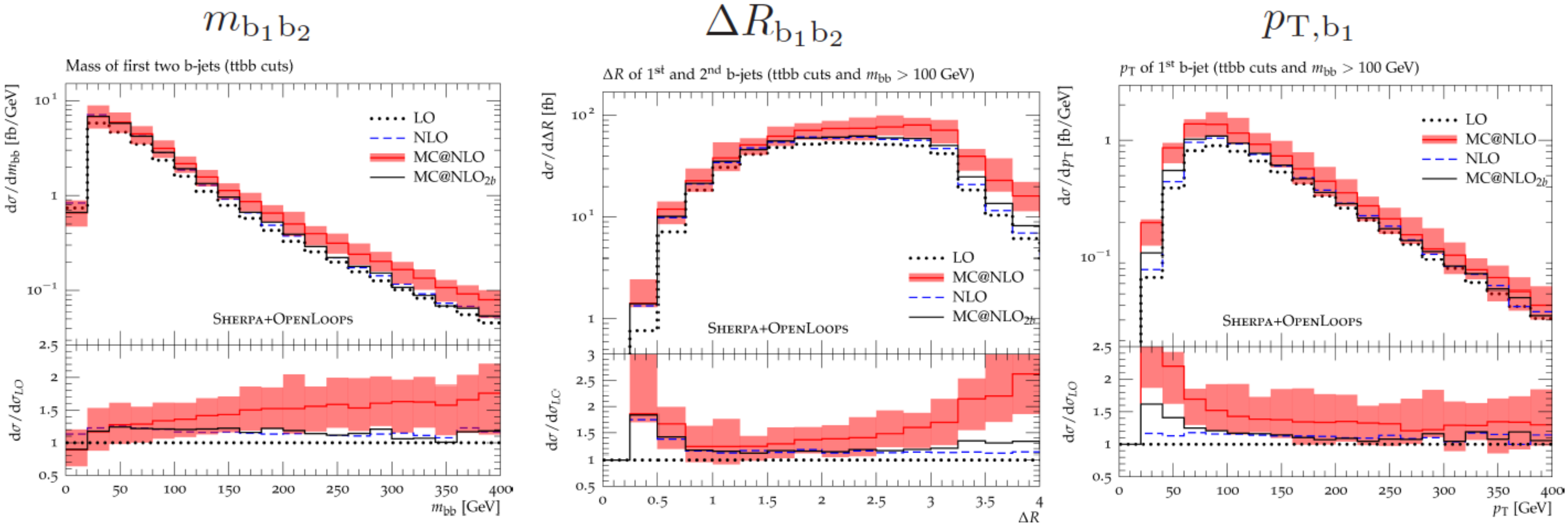
	ttb	$ttbb$	$ttbb\,(m_{bb} > 100)$
$\sigma_{\rm LO}\,[\rm fb]$	$2644^{+71\%\,+14\%}_{-38\%\,-11\%}$	$463.3^{+66\%\,+15\%}_{-36\%\,-12\%}$	$123.4^{+63\%\,+17\%}_{-35\%\,-13\%}$
$\sigma_{\rm NLO}\,[\rm fb]$	$3296^{+34\%\,+5.6\%}_{-25\%\,-4.2\%}$	$560^{+29\%\,+5.4\%}_{-24\%\,-4.8\%}$	$141.8^{+26\%\,+6.5\%}_{-22\%\,-4.6\%}$
$\sigma_{\rm NLO}/\sigma_{\rm LO}$	1.25	1.21	1.15
$\sigma_{\rm MC@NLO}\,[\rm fb]$	$3313^{+32\%\,+3.9\%}_{-25\%\,-2.9\%}$	$600^{+24\%\,+2.0\%}_{-22\%\,-2.1\%}$	$181^{+20\%\,+8.1\%}_{-20\%\,-6.0\%}$
$\sigma_{\rm MC@NLO}/\sigma_{\rm NLO}$	1.01	1.07	1.28

MSTW2008 NLO(LO) 4F PDFs

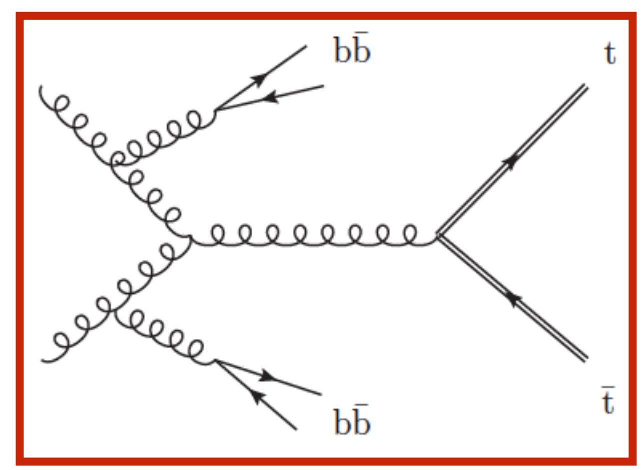
$\sigma_{\rm MC@NLO}/\sigma_{\rm NLO} \sim 30\%$ for $m_{bb} > 100$GeV!

ttH(→bb) in the Boosted Region

Cascioli, Maierhoefer, Moretti, Pozzorini, Siegert, 2013

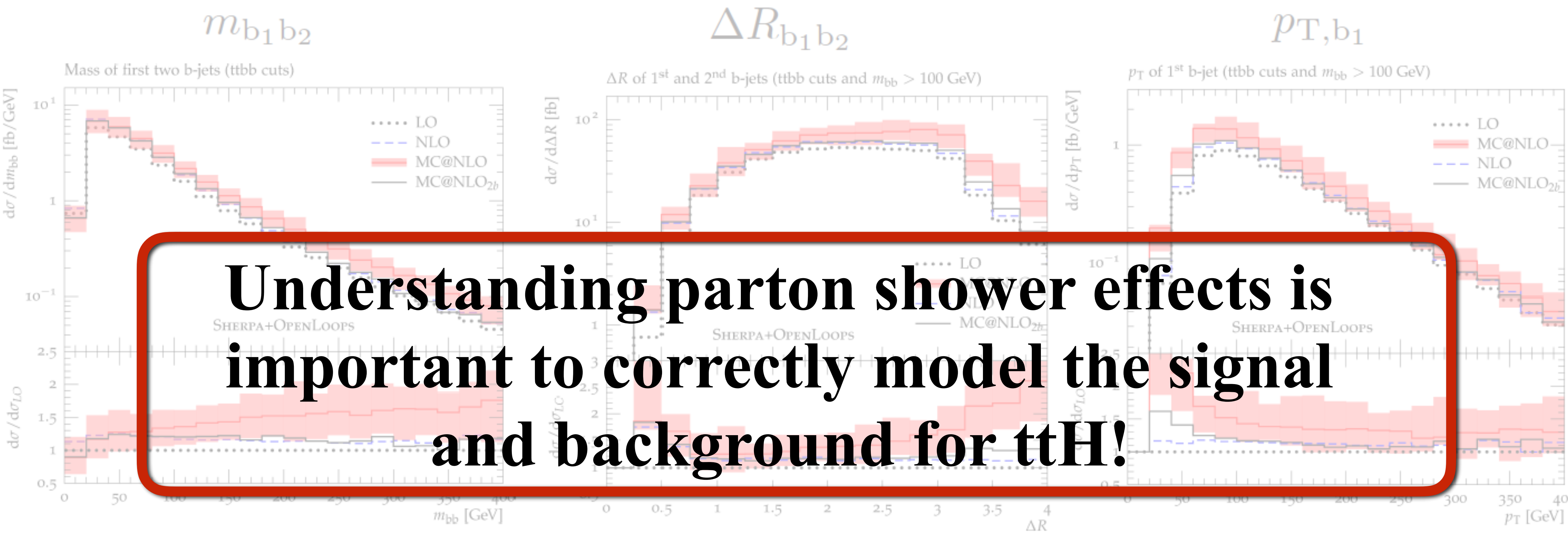


- MC@NLO enhancement at large m_{b1b2} ~125GeV, small $p_{T,b1}$ and ΔR_{b1b2}~π
- Enhancement disappears almost completely when g→bb splitting is switched off in shower ($MC@NLO_{2b}$) ➪ large correction from double g→bb splitting
- Important new effect beyond NLO that affects the prediction



ttH(→bb) in the Boosted Region

Cascioli, Maierhoefer, Moretti, Pozzorini, Siegert, 2013



Understanding parton shower effects is important to correctly model the signal and background for ttH!

- MC@NLO enhancement at large m_{b1b2} ~125GeV, small $p_{T,b1}$ and ΔR_{b1b2}~π
- Enhancement disappears almost completely when g→bb splitting is switched off in MC@NLO parton shower ⇨ MC@NLO$_{2b}$

Summary

> ASK NOT WHAT BIG CIRCULAR COLLIDERS CAN DO FOR YOU, ASK WHAT YOU CAN DO FOR BIG CIRCULAR COLLIDERS!

- Nima Arkani Hamed, Pheno conference 2016