Higher-order QCD calculations

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Apologies: A talk with many questions and no answers

Why is precision important

Precision can be a game changer for the HL/HE LHC physics programme

- when new particles are found directly precision measurements of properties, which are needed to understand the new underlying theory (this is happening now with the Higgs sector of the SM)
- but also precision tests bring in new possibilities of precision-driven discoveries, complementary to direct searches (e.g. like for the top quark at LEP)

Precision through perturbation

Three main tools to achieve precision

1. fixed order

$$\frac{\sigma}{\sigma_0} = 1 + c_1\alpha + c_2\alpha^2 + \ldots$$

1	LO
$+\, c_1\alpha$	NLO
$+\, c_2\alpha^2$	NNLO
$+\ldots$	

2. all order (L = large logarithm)

$$\ln\frac{\sigma}{\sigma_0} = \alpha^n L^{n+1} + \alpha^n L^n + \alpha^n L^{n-1} + \ldots$$

$\alpha^n L^{n+1}$	LL
$+\,\alpha^n L^n$	NLL
$+\,\alpha^n L^{n-1}$	NNLL
$+\ldots$	

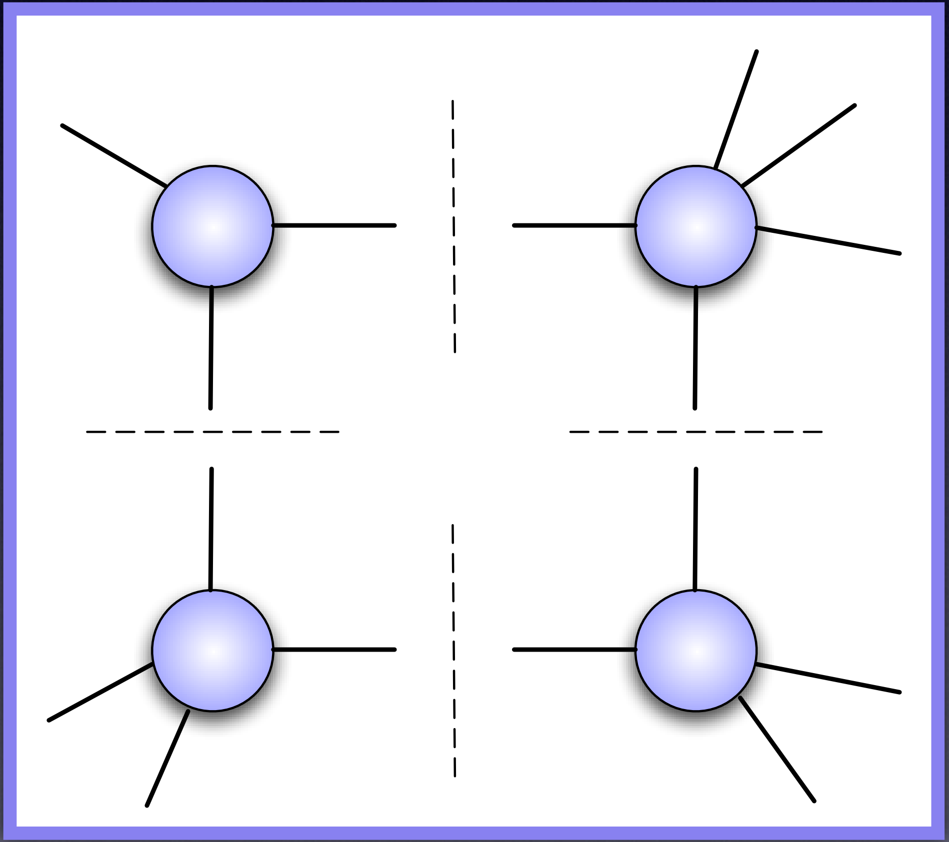
3. go from perturbative picture (quark/gluons) to realistic final state (pions, mesons etc.) using parton shower event generators

What is the status of precision calculations?

The NLO revolution

For a long time, the NLO calculation for each process required a separate non-trivial, manual calculation. Suddenly, **thanks to theoretical conceptual breakthrough ideas**

- input from supersymmetry/string theory
- connection between loop (NLO) amplitudes and tree (LO) ones
- sophisticated algebraic methods, OPP
- generalised unitarity



the problem of computing NLO QCD corrections is now solved

Automated NLO

<u>An example:</u> single Higgs production processes

Alwall et al '14

Process		Syntax	Cross section (pb)			
Single Higgs production			LO 13 TeV		NLO 13 TeV	
g.1	$pp \to H$ (HEFT)	`p p > h`	$1.593 \pm 0.003 \cdot 10^{1}$	${}^{+34.8\%}_{-26.0\%}$ ${}^{+1.2\%}_{-1.7\%}$	$3.261 \pm 0.010 \cdot 10^{1}$	${}^{+20.2\%}_{-17.9\%}$ ${}^{+1.1\%}_{-1.6\%}$
g.2	$pp \to Hj$ (HEFT)	`p p > h j`	$8.367 \pm 0.003 \cdot 10^{0}$	${}^{+39.4\%}_{-26.4\%}$ ${}^{+1.2\%}_{-1.4\%}$	$1.422 \pm 0.006 \cdot 10^{1}$	${}^{+18.5\%}_{-16.6\%}$ ${}^{+1.1\%}_{-1.4\%}$
g.3	$pp \to Hjj$ (HEFT)	`p p > h j j`	$3.020 \pm 0.002 \cdot 10^{0}$	${}^{+59.1\%}_{-34.7\%}$ ${}^{+1.4\%}_{-1.7\%}$	$5.124 \pm 0.020 \cdot 10^{0}$	${}^{+20.7\%}_{-21.0\%}$ ${}^{+1.3\%}_{-1.5\%}$
g.4	$pp \to Hjj$ (VBF)	`p p > h j j $$ w+ w- z`	$1.987 \pm 0.002 \cdot 10^{0}$	${}^{+1.7\%}_{-2.0\%}$ ${}^{+1.9\%}_{-1.4\%}$	$1.900 \pm 0.006 \cdot 10^{0}$	${}^{+0.8\%}_{-0.9\%}$ ${}^{+2.0\%}_{-1.5\%}$
g.5	$pp \to Hjjj$ (VBF)	`p p > h j j j $$ w+ w- z`	$2.824 \pm 0.005 \cdot 10^{-1}$	${}^{+15.7\%}_{-12.7\%}$ ${}^{+1.5\%}_{-1.0\%}$	$3.085 \pm 0.010 \cdot 10^{-1}$	${}^{+2.0\%}_{-3.0\%}$ ${}^{+1.5\%}_{-1.1\%}$
g.6	$pp \to HW^{\pm}$	`p p > h wpm`	$1.195 \pm 0.002 \cdot 10^{0}$	${}^{+3.5\%}_{-4.5\%}$ ${}^{+1.9\%}_{-1.5\%}$	$1.419 \pm 0.005 \cdot 10^{0}$	${}^{+2.1\%}_{-2.6\%}$ ${}^{+1.9\%}_{-1.4\%}$
g.7	$pp \to HW^{\pm}j$	`p p > h wpm j`	$4.018 \pm 0.003 \cdot 10^{-1}$	${}^{+10.7\%}_{-9.3\%}$ ${}^{+1.2\%}_{-0.9\%}$	$4.842 \pm 0.017 \cdot 10^{-1}$	${}^{+3.6\%}_{-3.7\%}$ ${}^{+1.2\%}_{-1.0\%}$
g.8*	$pp \to HW^{\pm}jj$	`p p > h wpm j j`	$1.198 \pm 0.016 \cdot 10^{-1}$	${}^{+26.1\%}_{-19.4\%}$ ${}^{+0.8\%}_{-0.6\%}$	$1.574 \pm 0.014 \cdot 10^{-1}$	${}^{+5.0\%}_{-6.5\%}$ ${}^{+0.9\%}_{-0.6\%}$
g.9	$pp \to HZ$	`p p > h z`	$6.468 \pm 0.008 \cdot 10^{-1}$	${}^{+3.5\%}_{-4.5\%}$ ${}^{+1.9\%}_{-1.4\%}$	$7.674 \pm 0.027 \cdot 10^{-1}$	${}^{+2.0\%}_{-2.5\%}$ ${}^{+1.9\%}_{-1.4\%}$
g.10	$pp \to HZj$	`p p > h z j`	$2.225 \pm 0.001 \cdot 10^{-1}$	${}^{+10.6\%}_{-9.2\%}$ ${}^{+1.1\%}_{-0.8\%}$	$2.667 \pm 0.010 \cdot 10^{-1}$	${}^{+3.5\%}_{-3.6\%}$ ${}^{+1.1\%}_{-0.9\%}$
g.11*	$pp \to HZjj$	`p p > h z j j`	$7.262 \pm 0.012 \cdot 10^{-2}$	${}^{+26.2\%}_{-19.4\%}$ ${}^{+0.7\%}_{-0.6\%}$	$8.753 \pm 0.037 \cdot 10^{-2}$	${}^{+4.8\%}_{-6.3\%}$ ${}^{+0.7\%}_{-0.6\%}$
g.12*	$pp \to HW^{+}W^{-}$ (4f)	`p p > h w+ w-`	$8.325 \pm 0.139 \cdot 10^{-3}$	${}^{+0.0\%}_{-0.3\%}$ ${}^{+2.0\%}_{-1.6\%}$	$1.065 \pm 0.003 \cdot 10^{-2}$	${}^{+2.5\%}_{-1.9\%}$ ${}^{+2.0\%}_{-1.5\%}$
g.13*	$pp \to HW^{\pm}\gamma$	`p p > h wpm a`	$2.518 \pm 0.006 \cdot 10^{-3}$	${}^{+0.7\%}_{-1.4\%}$ ${}^{+1.9\%}_{-1.5\%}$	$3.309 \pm 0.011 \cdot 10^{-3}$	${}^{+2.7\%}_{-2.0\%}$ ${}^{+1.7\%}_{-1.4\%}$
g.14*	$pp \to HZW^{\pm}$	`p p > h z wpm`	$3.763 \pm 0.007 \cdot 10^{-3}$	${}^{+1.1\%}_{-1.5\%}$ ${}^{+2.0\%}_{-1.6\%}$	$5.292 \pm 0.015 \cdot 10^{-3}$	${}^{+3.9\%}_{-3.1\%}$ ${}^{+1.8\%}_{-1.4\%}$
g.15*	$pp \to HZZ$	`p p > h z z`	$2.093 \pm 0.003 \cdot 10^{-3}$	${}^{+0.1\%}_{-0.6\%}$ ${}^{+1.9\%}_{-1.5\%}$	$2.538 \pm 0.007 \cdot 10^{-3}$	${}^{+1.9\%}_{-1.4\%}$ ${}^{+2.0\%}_{-1.5\%}$
g.16	$pp \to Ht\bar{t}$	`p p > h t t~`	$3.579 \pm 0.003 \cdot 10^{-1}$	${}^{+30.0\%}_{-21.5\%}$ ${}^{+1.7\%}_{-2.0\%}$	$4.608 \pm 0.016 \cdot 10^{-1}$	${}^{+5.7\%}_{-9.0\%}$ ${}^{+2.0\%}_{-2.3\%}$
g.17	$pp \to Htj$	`p p > h tt j`	$4.994 \pm 0.005 \cdot 10^{-2}$	${}^{+2.4\%}_{-4.2\%}$ ${}^{+1.2\%}_{-1.3\%}$	$6.328 \pm 0.022 \cdot 10^{-2}$	${}^{+2.9\%}_{-1.8\%}$ ${}^{+1.5\%}_{-1.6\%}$
g.18	$pp \to Hb\bar{b}$ (4f)	`p p > h b b~`	$4.983 \pm 0.002 \cdot 10^{-1}$	${}^{+28.1\%}_{-21.0\%}$ ${}^{+1.5\%}_{-1.8\%}$	$6.085 \pm 0.026 \cdot 10^{-1}$	${}^{+7.3\%}_{-9.6\%}$ ${}^{+1.6\%}_{-2.0\%}$
g.19	$pp \to Ht\bar{t}j$	`p p > h t t~ j`	$2.674 \pm 0.041 \cdot 10^{-1}$	${}^{+45.6\%}_{-29.2\%}$ ${}^{+2.6\%}_{-2.9\%}$	$3.244 \pm 0.025 \cdot 10^{-1}$	${}^{+3.5\%}_{-8.7\%}$ ${}^{+2.5\%}_{-2.9\%}$
g.20*	$pp \to Hb\bar{b}j$ (4f)	`p p > h b b~ j`	$7.367 \pm 0.002 \cdot 10^{-2}$	${}^{+45.6\%}_{-29.1\%}$ ${}^{+1.8\%}_{-2.1\%}$	$9.034 \pm 0.032 \cdot 10^{-2}$	${}^{+7.9\%}_{-11.0\%}$ ${}^{+1.8\%}_{-2.2\%}$

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Similar results available for all SM processes of similar complexity

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NLO calculations

Various (public) tools developed: Blackhat+Sherpa, GoSam+Sherpa, Helac-NLO, Madgraph5_aMC@NLO, NJet+Sherpa, OpenLoops+Sherpa, Samurai, Recola ...

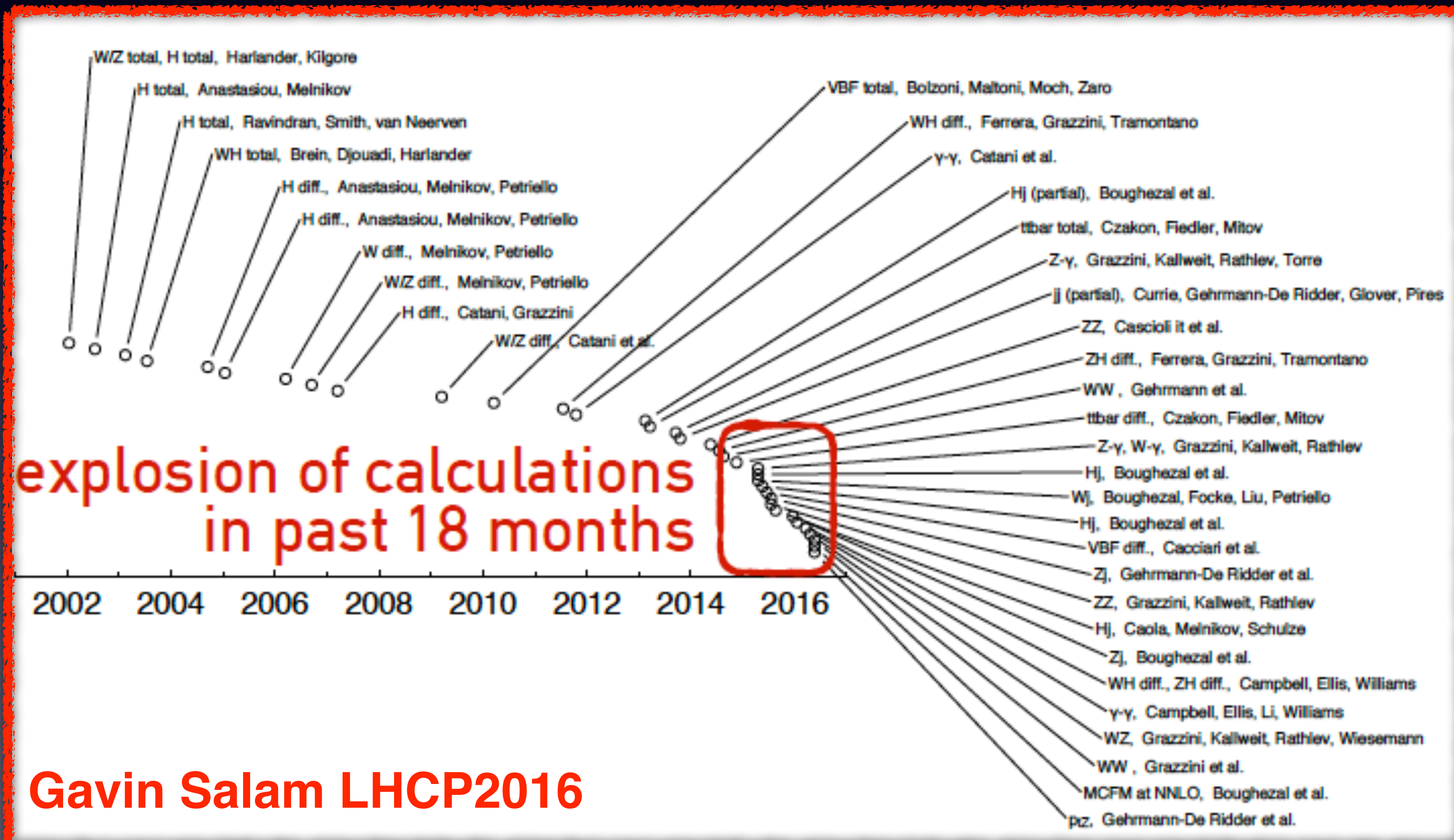
- Practical limitation: high-multiplicity processes still difficult because of numerical instabilities, need long run-time on clusters to obtain stable results (edge: 5-6 particles in the final state, depending on the process)
- Today focus on
  - ➡ automation of NLO for BSM signals
  - ➡ loop-induced processes: formally higher-order, but enhanced by gluon PDF
  - ➡ automation of NLO electroweak corrections (necessary to match accuracy of NNLO)

See talk by Maltoni

Precision of NLO (about 10-50%) is in many cases not enough to match current experimental precision, let alone the projected one at $3ab^{-1}$

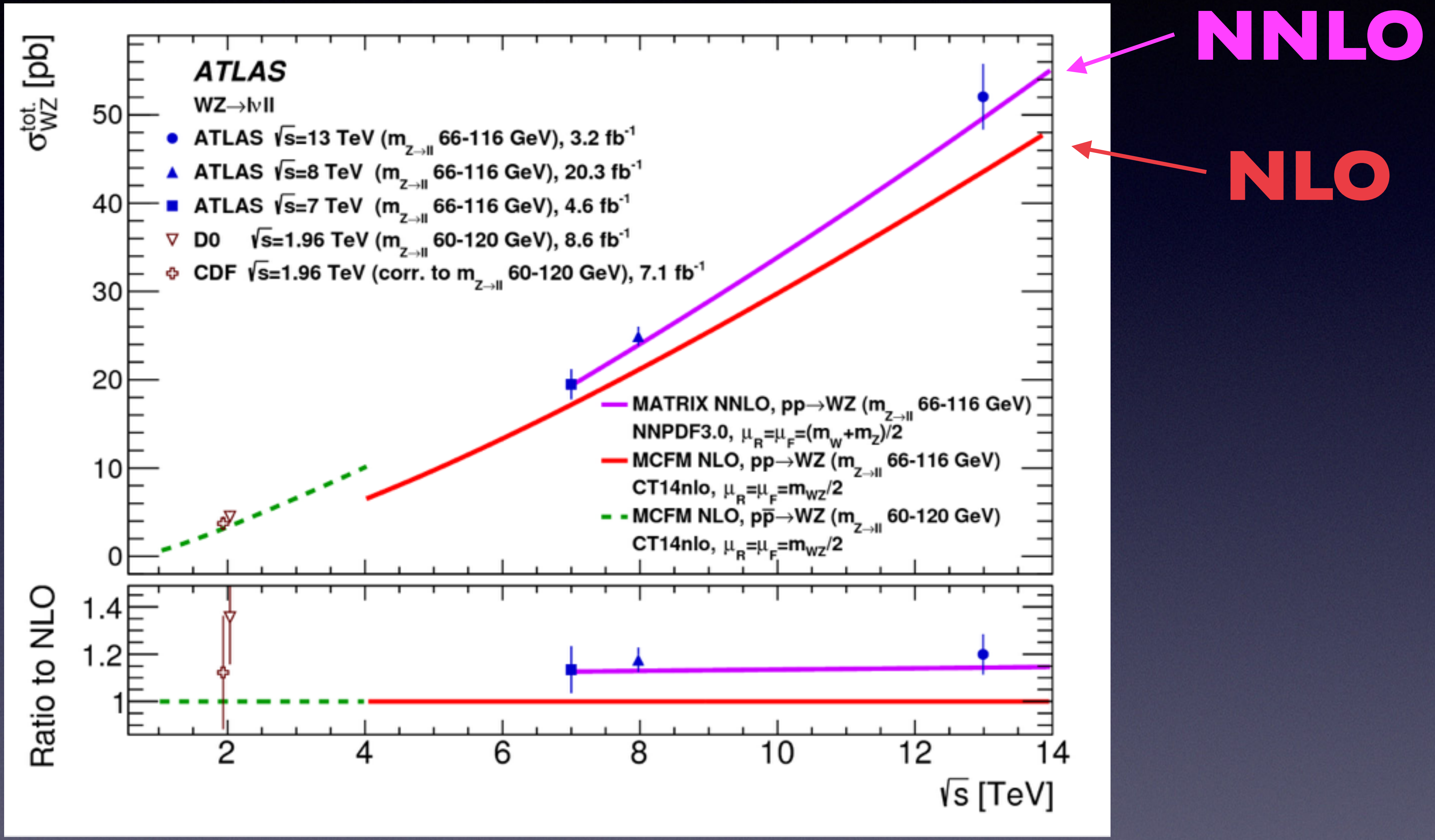
Status of NNLO

- ☑ Every SM 2 to 2 process known at NNLO
- ☐ No (true) 2 to 3 process known at NNLO



Caveats and limitations: see later

NNLO vs data



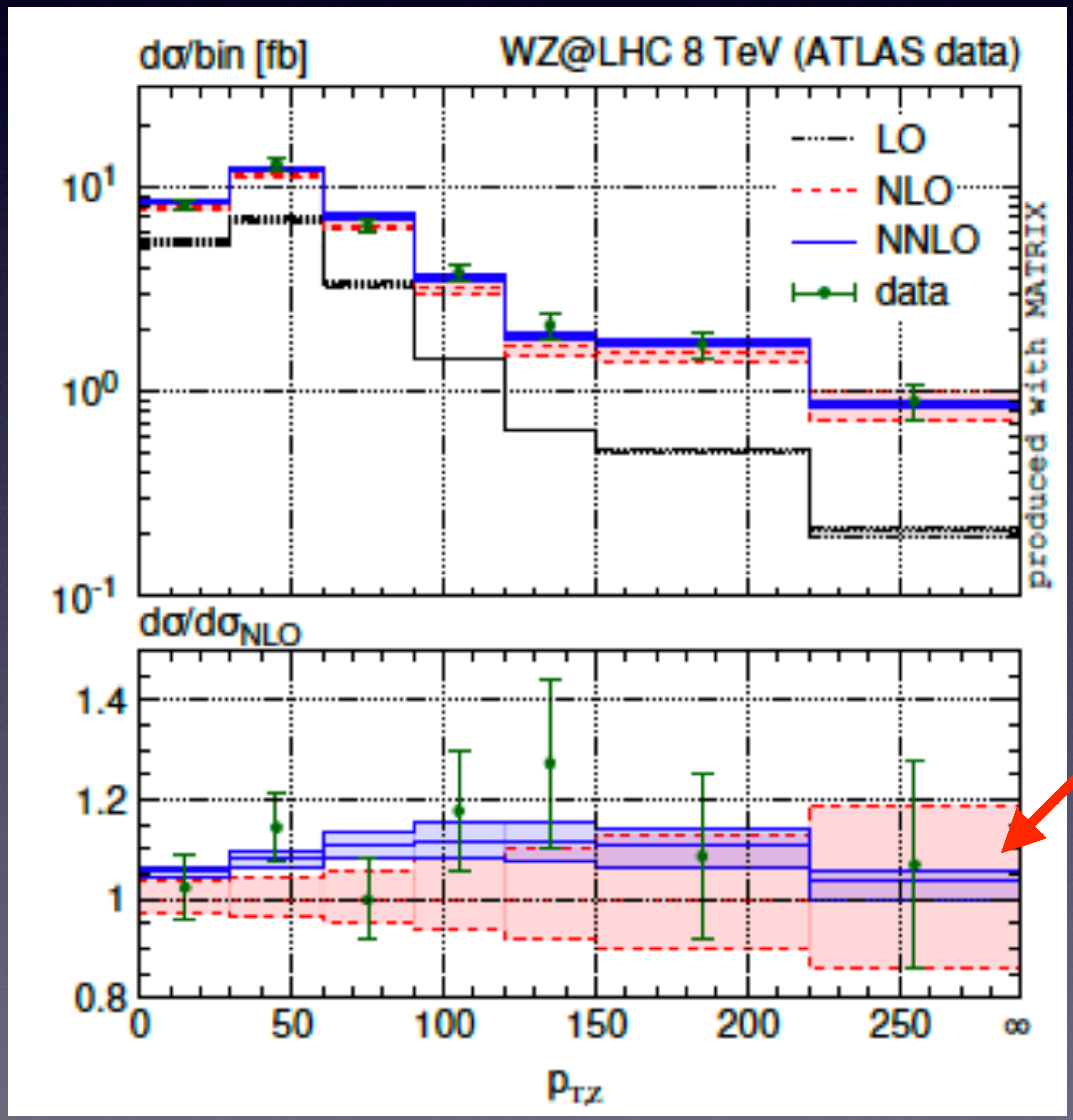
LHC data clearly prefers NNLO

Same conclusion in all measurements examined so far

With more data NLO certainly insufficient

VV production at NNLO

Example: NNLO WZ production vs current ATLAS data



- LO insufficient
- NNLO: 5-15% at larger p_t
- Moderate shape distortions from NLO to NNLO
- NNLO scale uncertainty of 5% up to high p_t (even smaller uncertainties in ratios)
- EW corrections (known) important in tails

See talks by Wiesemann, Lee, Schoenherr

VV production at NNLO

Example: WZ production in New physics search setup

channel	σ_{LO} [fb]	σ_{NLO} [fb]	σ_{NNLO} [fb]	$\sigma_{\mathrm{NLO}}/\sigma_{\mathrm{LO}}-1$	$\sigma_{\mathrm{NNLO}}/\sigma_{\mathrm{NLO}}-1$
			Category I		
combined	$162.2(0)^{+5.0\%}_{-6.0\%}$	$313.9(1)^{+4.9\%}_{-4.0\%}$	$353.7(3)^{+2.2\%}_{-2.2\%}$	93.5%	12.7%
			Category II		
combined	$1.026(0)^{+2.7\%}_{-2.8\%}$	$4.015(1)^{+13\%}_{-10\%}$	$4.911(3)^{+4.9\%}_{-5.2\%}$	292%	22.3%

More inclusive cuts

High-p_t search region

See talks by Wiesemann, Lee, Schoenherr

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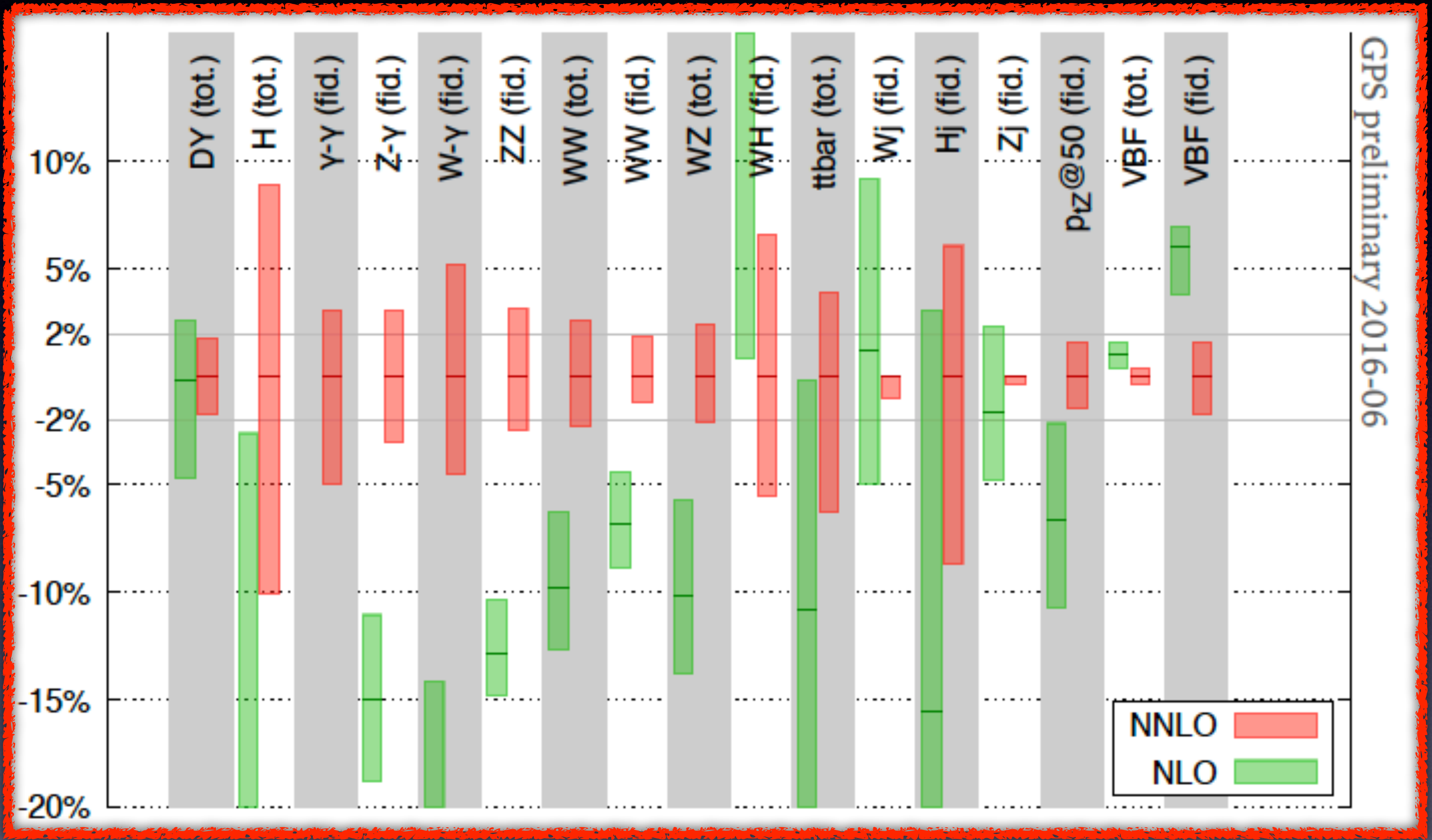
More inclusive cuts

High-p_t search region

What is the overall theory uncertainty in the intermediate and high-p_t region (relevant for EFT coupling constraints)?

See talks by Wiesemann, Lee, Schoenherr

Status of NNLO

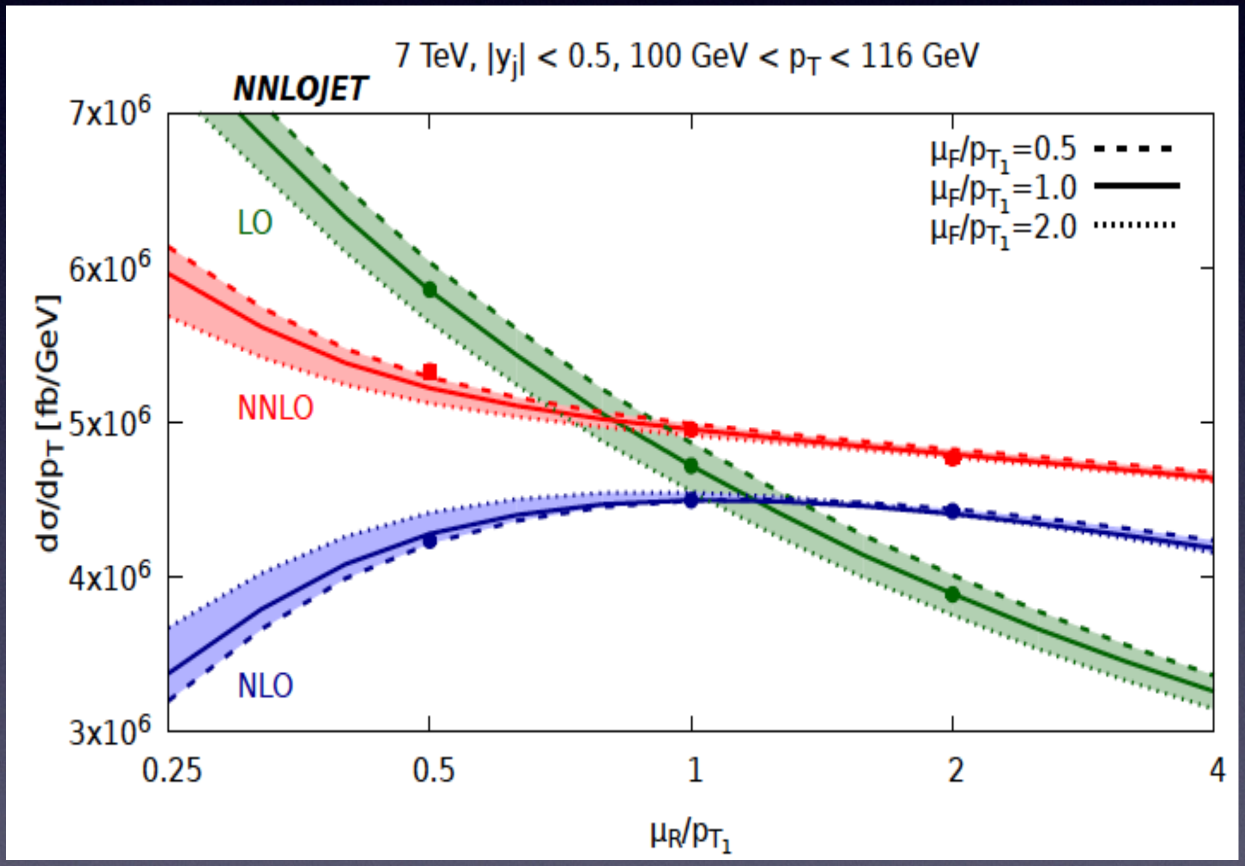


NNLO ***scale*** uncertainty bands of 1-2%.

Is the ***theory*** uncertainty indeed 1-2%?

Example: inclusive jet spectrum

Scale (μ_R, μ_F) : p_t of leading jet



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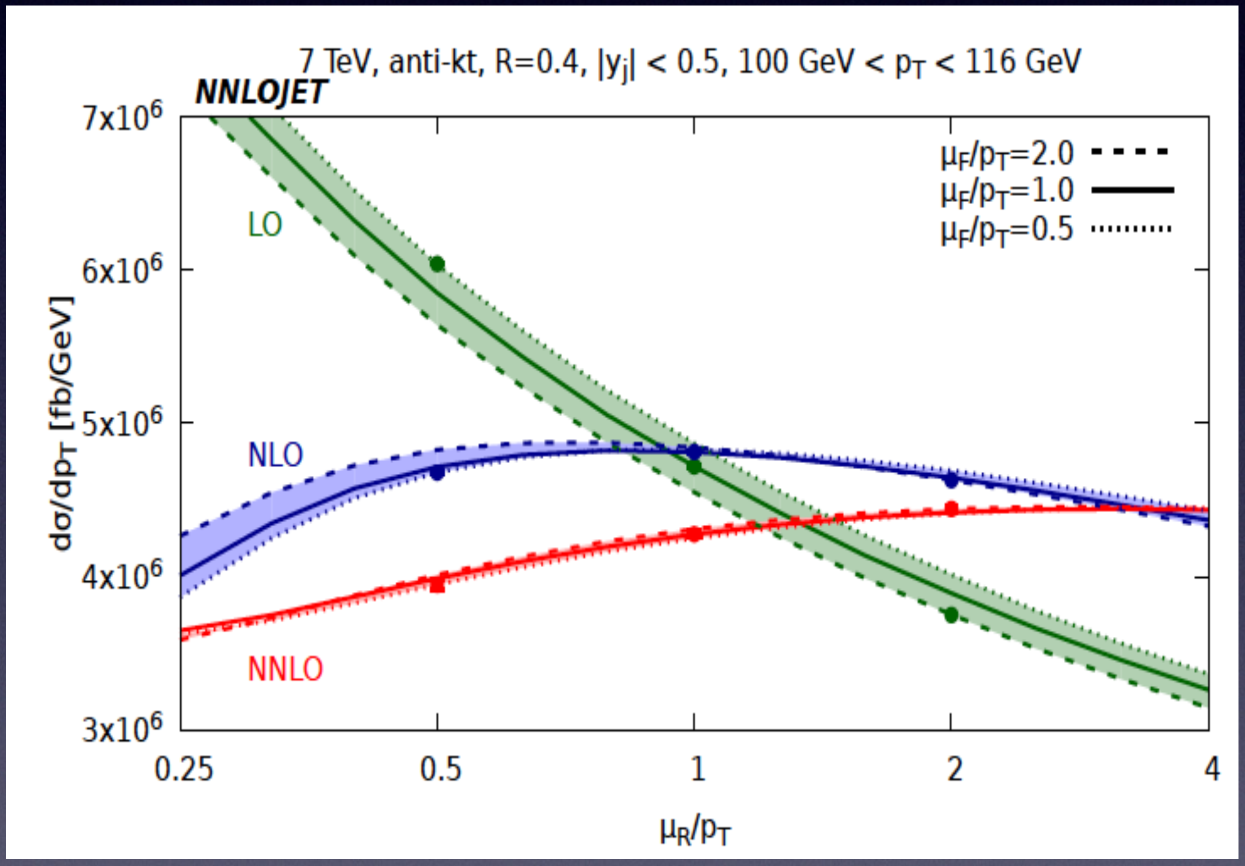

Currie, Glover, Pires 1611.01460

Low transverse momentum region

Example: inclusive jet spectrum

Scale (μ_R,μ_F) : p_t of leading jet

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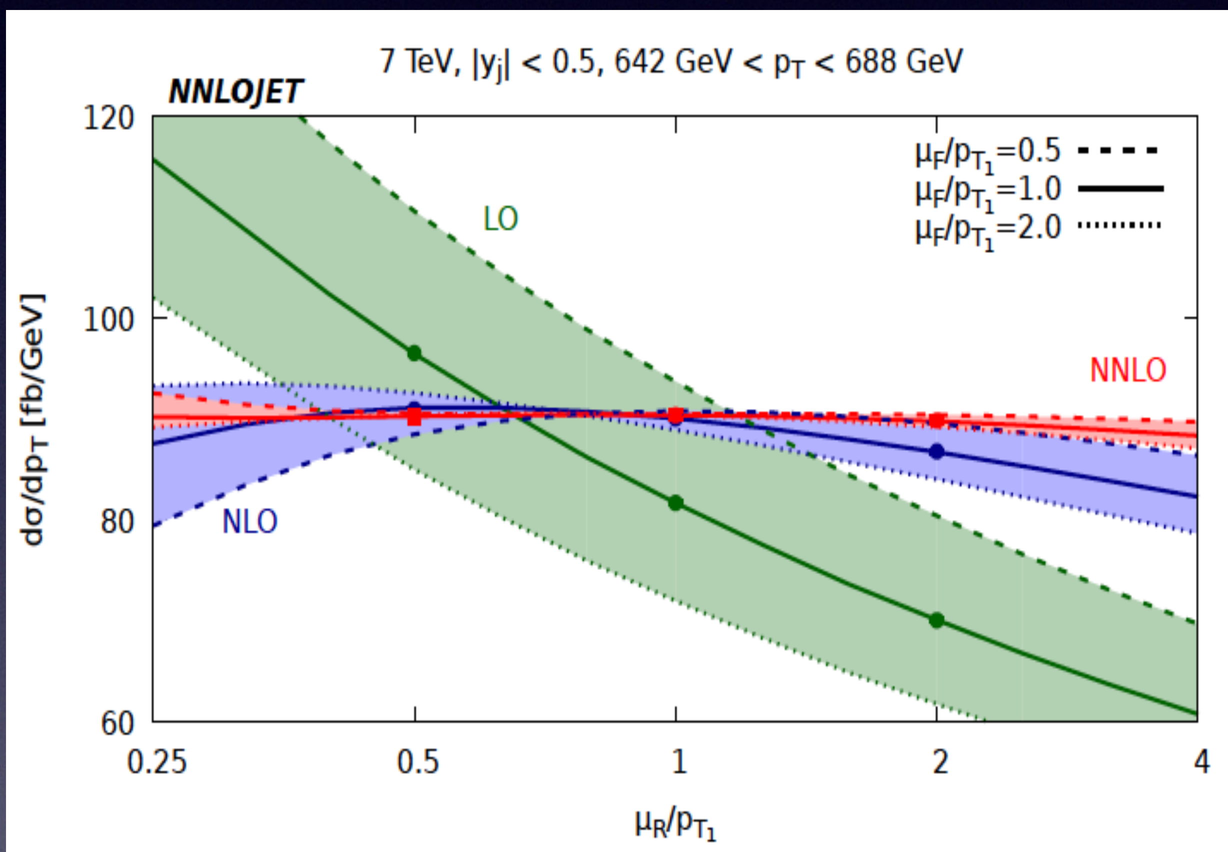
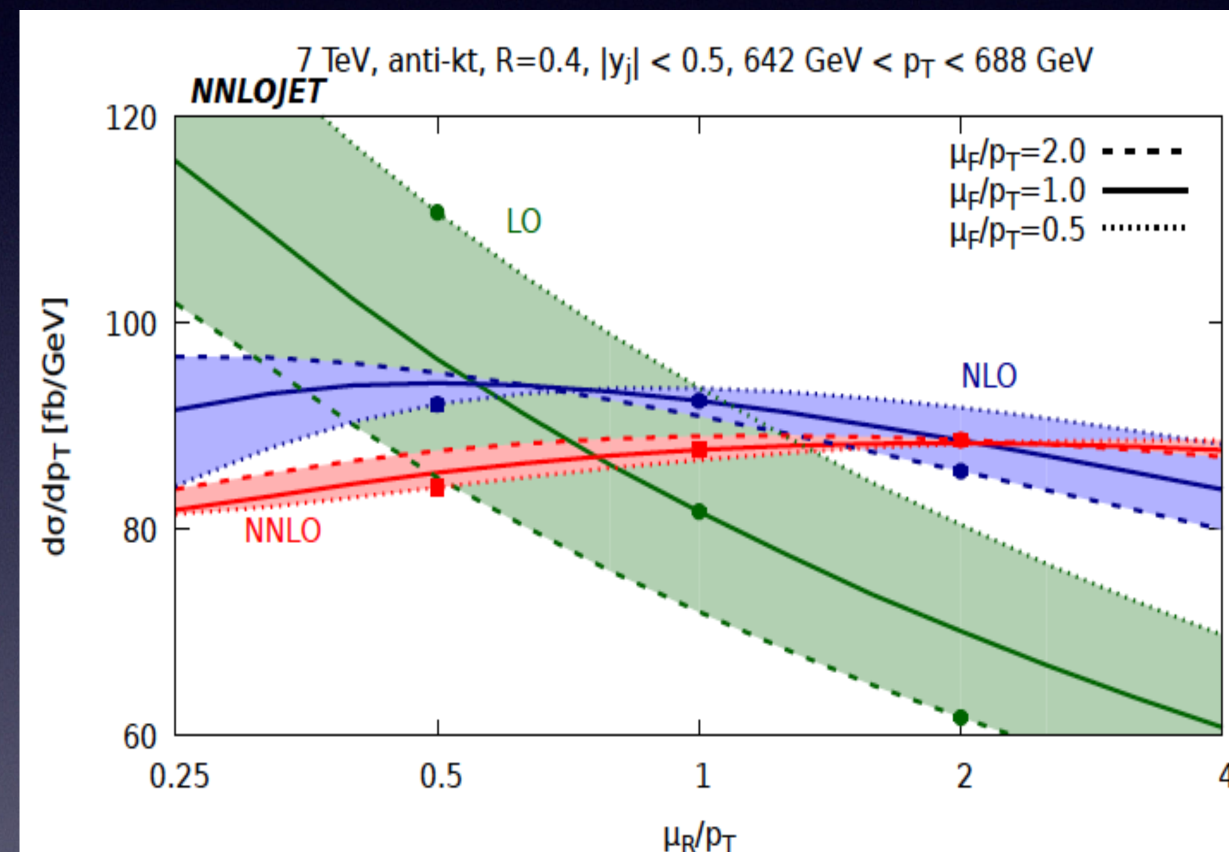


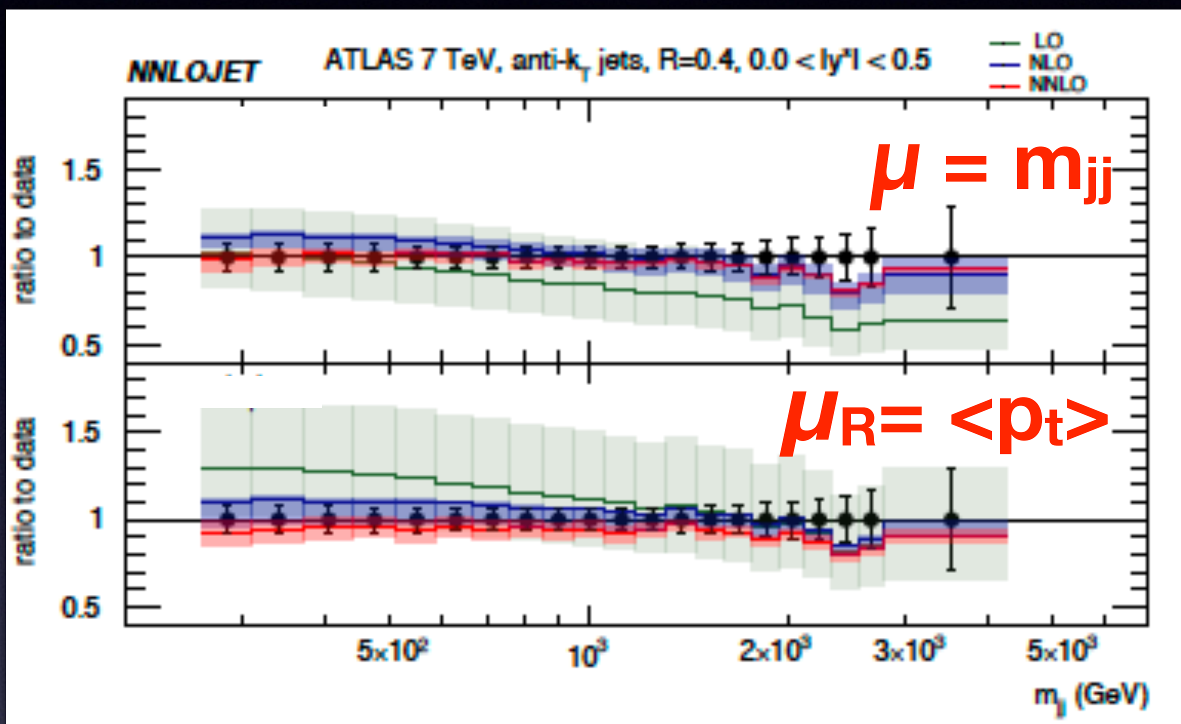


Currie, Glover, Pires 1611.01460

High transverse momentum region

Di-jet invariant mass

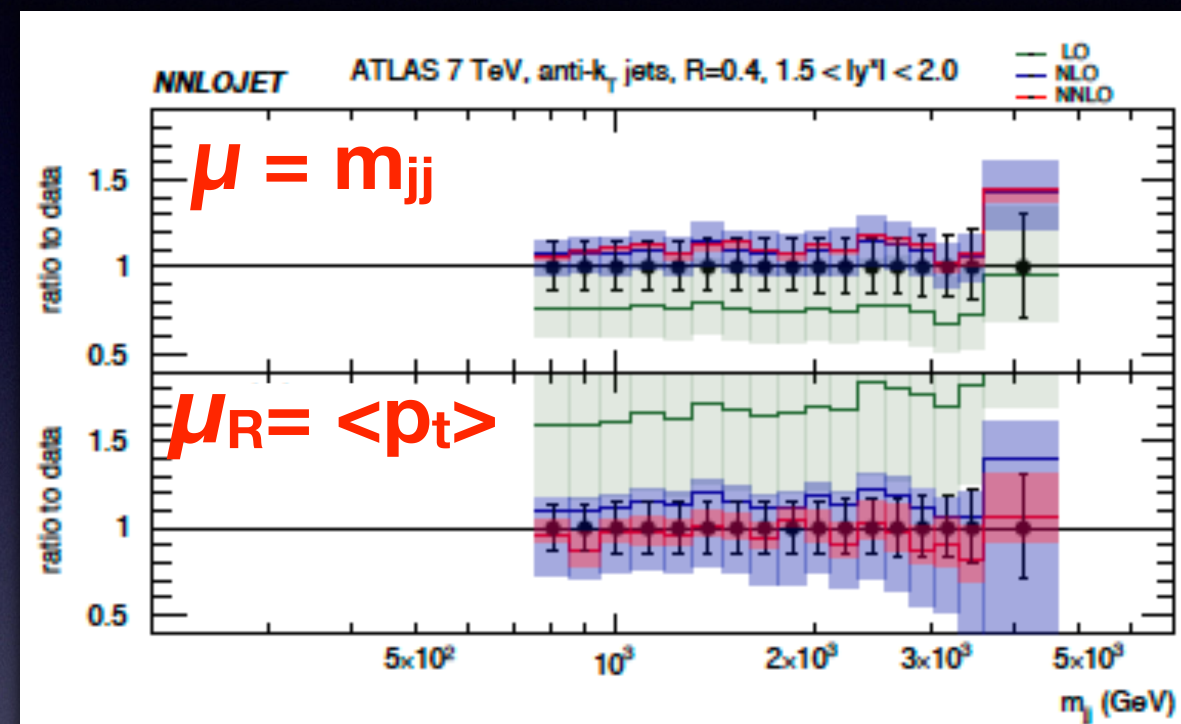
Small y_1-y_2



$2p_t \lesssim m_{jj} \lesssim 3p_t$ (LO)

⇒ p_t and m_{jj} scales similar

Larger y_1-y_2



$9p_t \lesssim m_{jj} \lesssim 15p_t$ (LO)

⇒ p_t and m_{jj} very different

"We choose the dijet invariant mass as the theoretical scale on the grounds of perturbative convergence and residual scale variation …"

Currie, A. Gehrmann-De Ridder, Gehrmann, Glover, Huss, Pires 1705.10271

Top unique in the SM:

- decays before hadronizing ⇨ direct access to bare quark
- heavy ⇨ window to New Physics

Differential NNLO results now available in the stable top approximation

Czakon, Fiedler, Heynes, Mitov 1601.05375
Czakon, Heynes, Mitov 1704.08551

- Non-trivial (and often overlooked) problem: difference between various dynamic scales can be substantial.
- This is now well-understood for inclusive top-pair production
- Criteria for fixing the scales:

arXiv:1606.03350

$$\mu_0 = \begin{cases} \frac{m_T}{2} & \text{for :} \quad p_{T,t},\ p_{T,\bar{t}} \text{ and } p_{T,t/\bar{t}}\,, \\ \frac{H_T}{4} & \text{for :} \quad \text{all other distributions}\,. \end{cases}$$

- Require minimal K-factors, both at NLO and NNLO and for the full kinematics

Mitov QCD@LHC2017

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Fiedler, Heynes, Mitov 1601.05375
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But no understanding of differences between $m_T/2$ and $H_T/4$

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- Require minimal K-factors, both at NLO and NNLO and for the full kinematics

Mitov QCD@LHC2017

Is the resulting uncertainty band reliable?

Scale setting

- *How should one set the renormalization and factorization scale in a given process? It is fair to set the scale a posteriori …?*
- *Can one trust the scale uncertainty band, i.e.the factor two variation around central scale [in particular if set a posteriori]?*
- *How should the scale uncertainty be interpreted? as a flat 100% interval* or as a 1σ (3σ?,5σ?) gaussian …?*

(*) Scale uncertainty interpreted as a 100% flat interval e.g. in the N3LO Higgs cross-section in the HXSWG and in the first extraction of α_s from ttbar at the LHC

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Do we need to revisit the procedure to assign a theory uncertainty to perturbative calculations?

(*) Scale uncertainty interpreted as a 100% flat interval e.g. in the N3LO Higgs cross-section in the HXSWG and in the first extraction of α_s from ttbar at the LHC

N^3LO

Two LHC processes known at N^3LO

- ✓ Gluon fusion Higgs production (in the limit of infinite top-quark mass)

  Anastasiou et al. 1503.06056, 1602.00695

- ✓ Vector boson fusion Higgs production (in the structure function approximation, i.e. double DIS process)

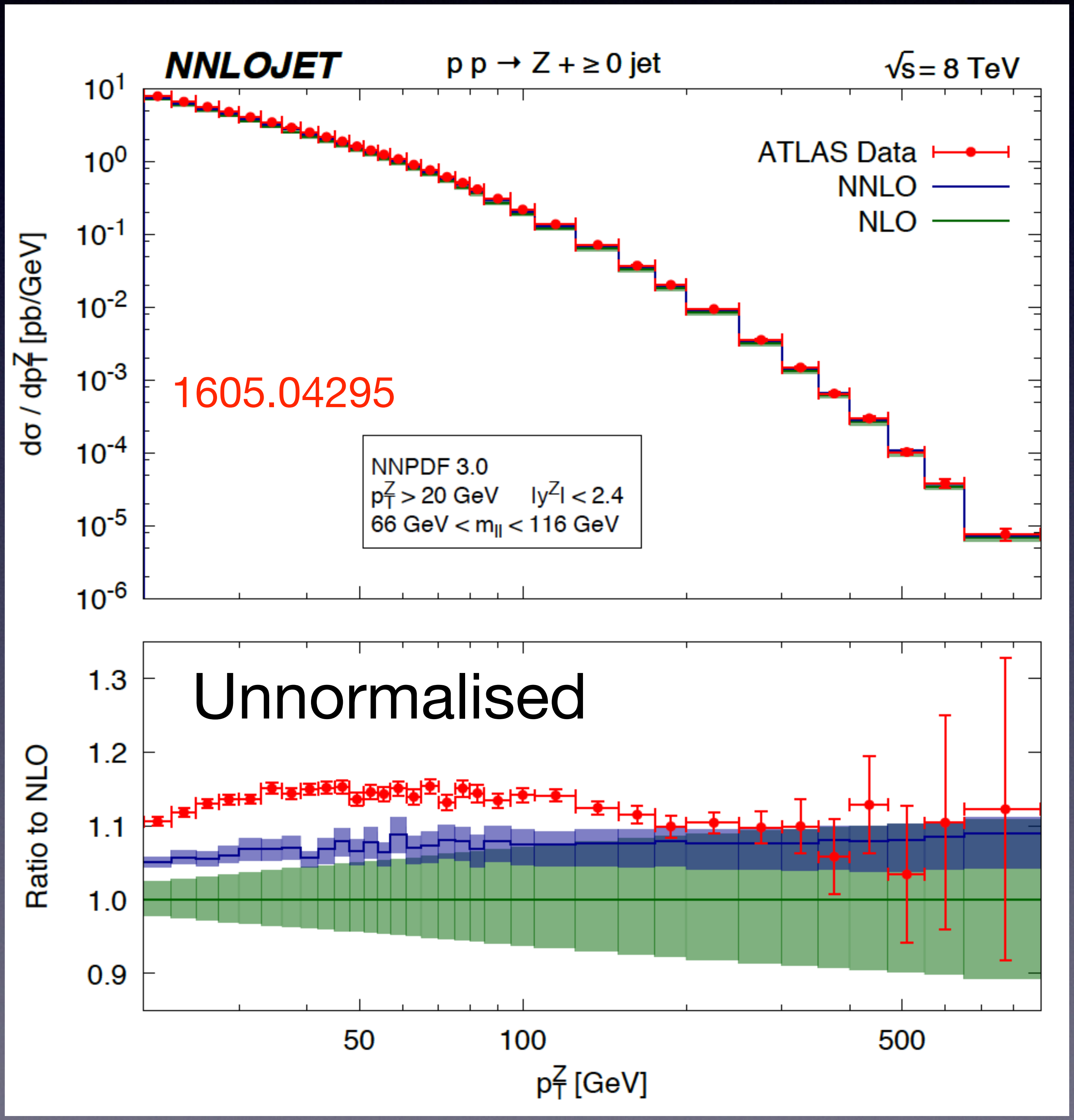
  Dreyer & Karlberg 1606.00840

In both cases, the NNLO was outside the NLO uncertainty band, while N^3LO band (with sensible scale) is fully inside the NNLO band.

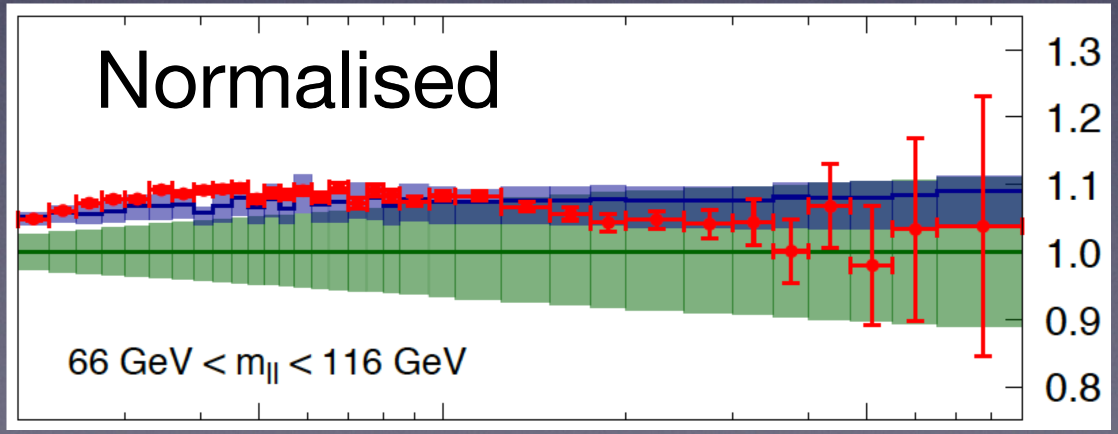
But there is **still no N^3LO result with realistic, fiducial cuts**

NNLO vs data for Z + jet

Gehrmann-De Ridder, Gehrmann, Glover, Huss, Morgan '16
Boughezal, Liu, Petriello '16
Boughezal, Ellis, Focke, Giele, Liu, Petriello '15

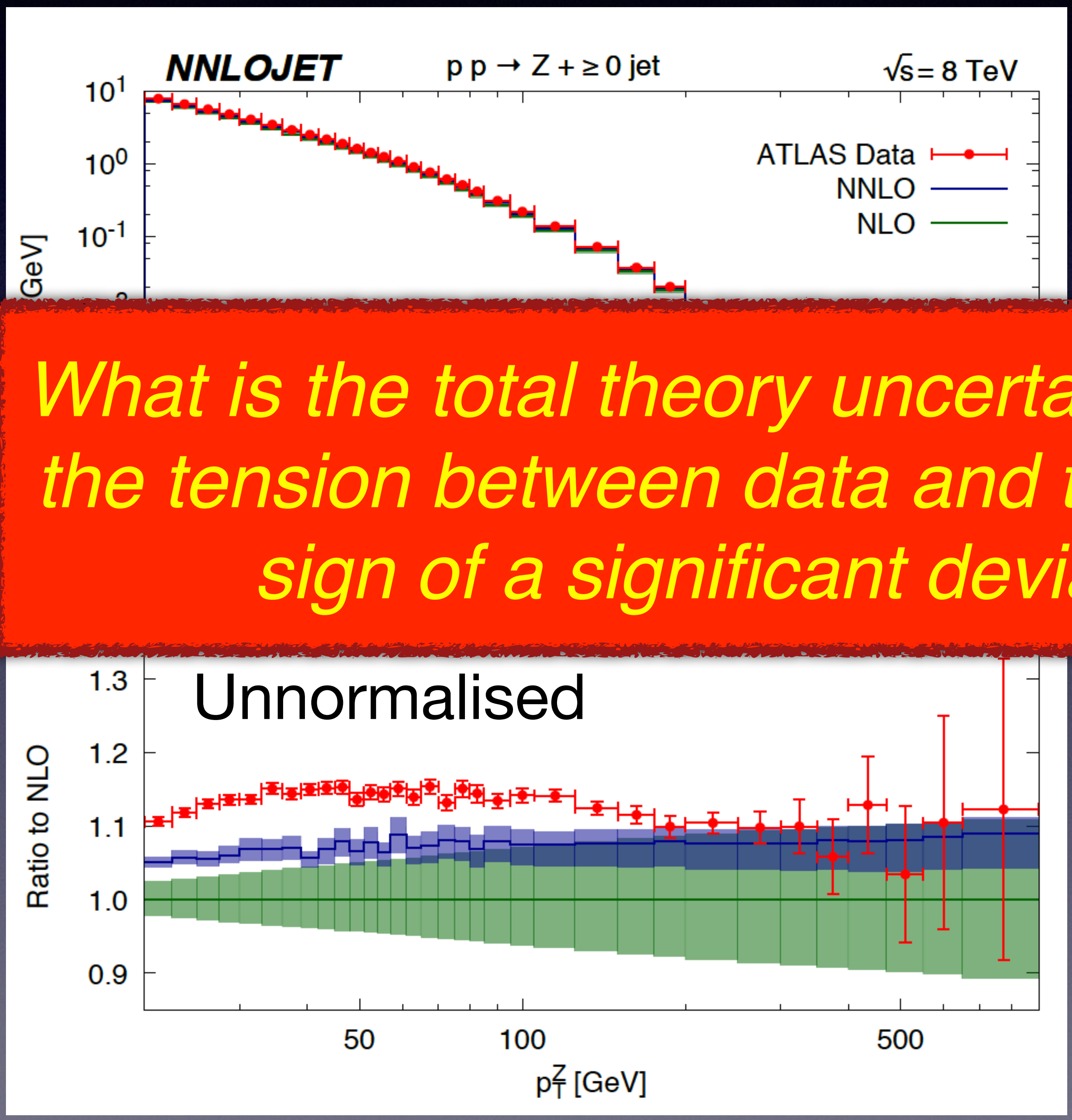


- NNLO and EW alleviate tension between data and theory
- better agreement in normalised distribution
- remember 2-3% luminosity error on data



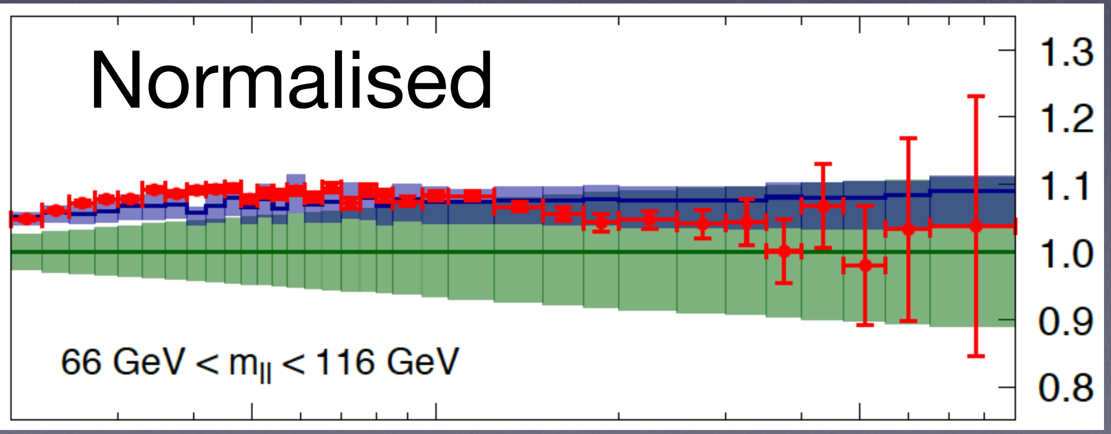
NNLO vs data for Z + jet

Gehrmann-De Ridder, Gehrmann, Glover, Huss, Morgan ’16
Boughezal, Liu, Petriello ’16
Boughezal, Ellis, Focke, Giele, Liu, Petriello ’15



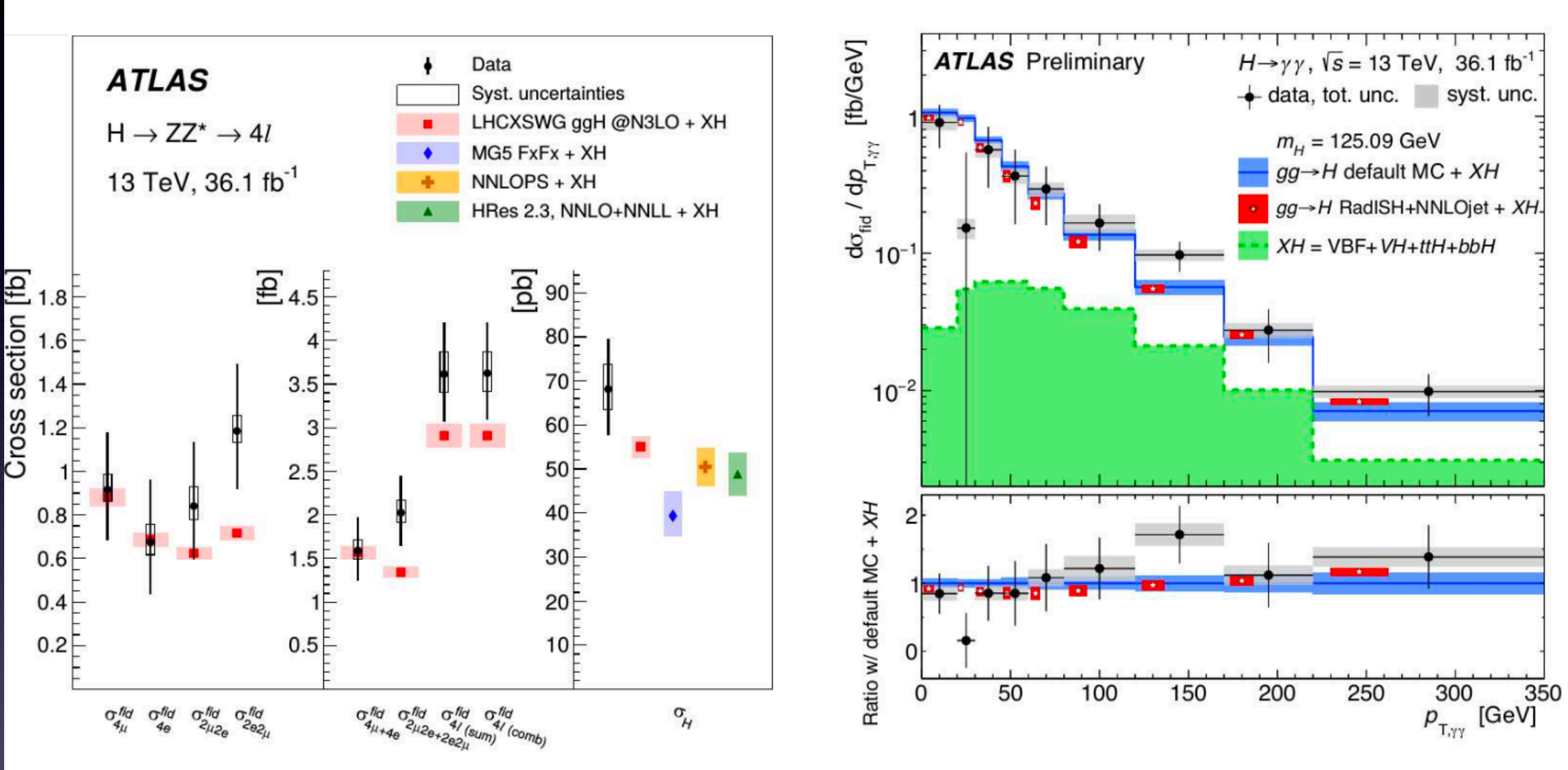
- NNLO and EW alleviate tension between data and th…

luminosity error on data



What is the total theory uncertainty? At which point could the tension between data and theory be interpreted as a sign of a significant deviation from the SM?

Higgs plus one jet



H→ZZ*→4ℓ

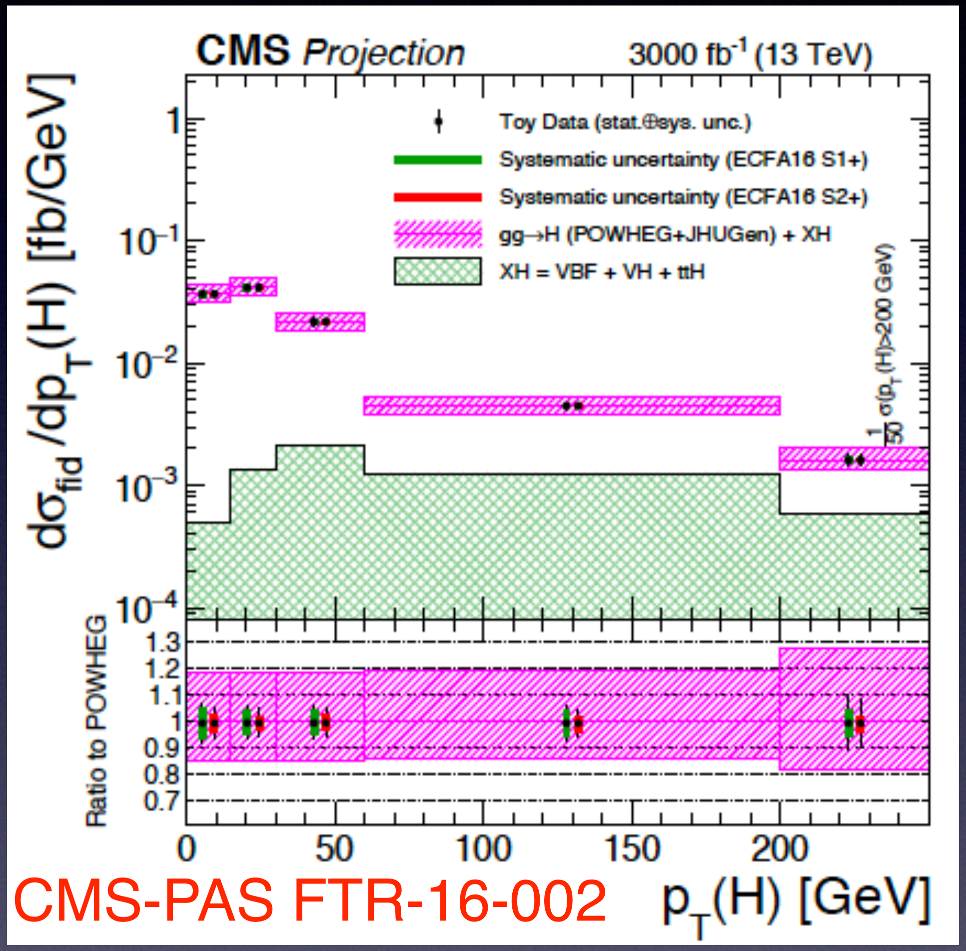
ATLAS, arXiv:1708.02810

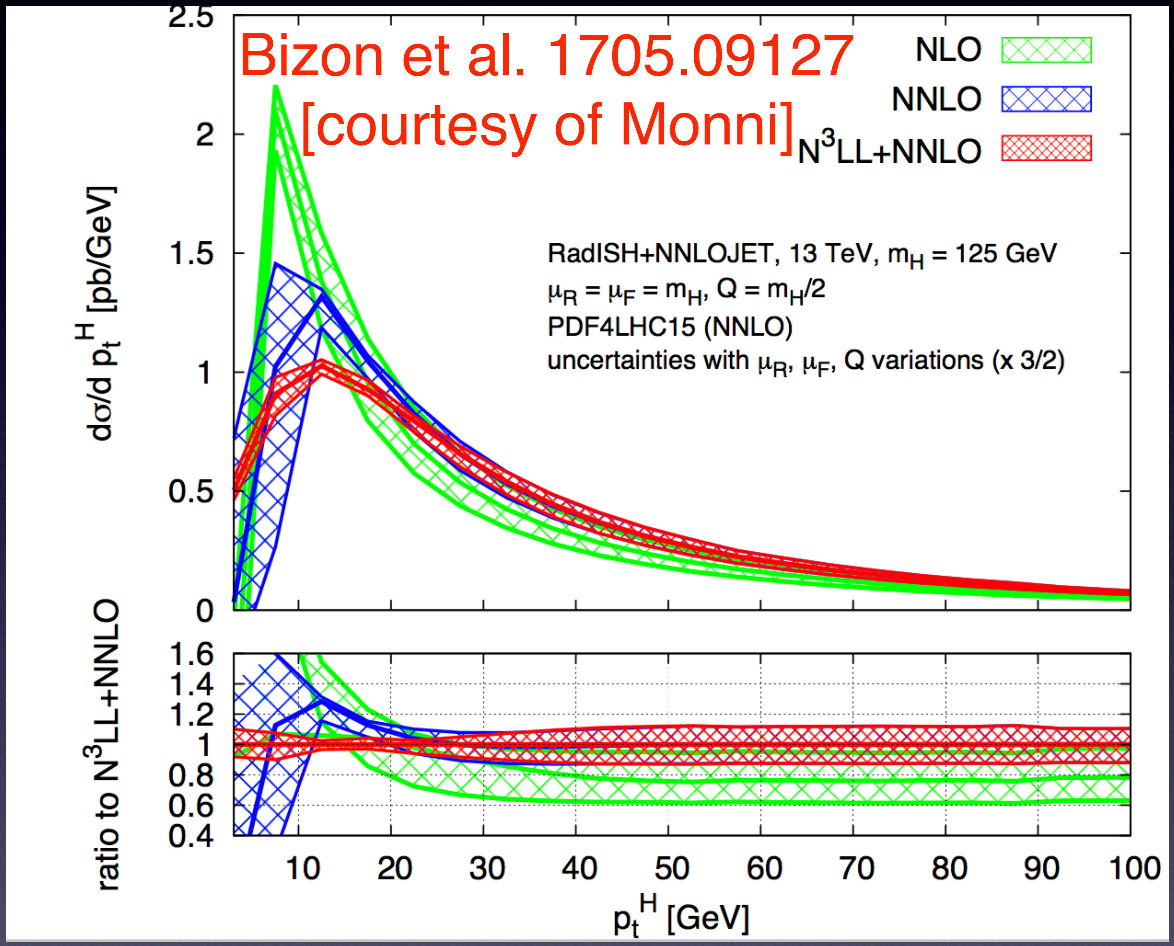
H→γγ

ATLAS-CONF-2017-045

- Better agreement with theory with 13 TeV data compared to 8 TeV
- NNLO predictions for fiducial cross-sections and merging to parton showers crucial

Projections for Higgs p_t

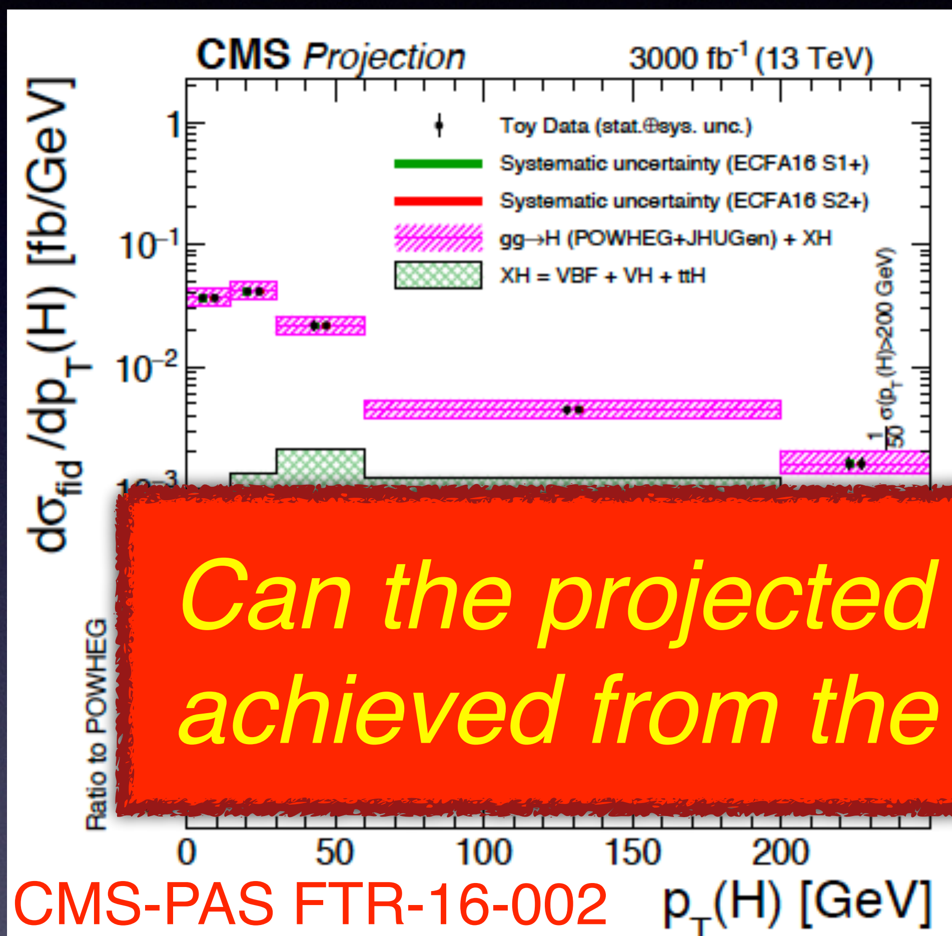


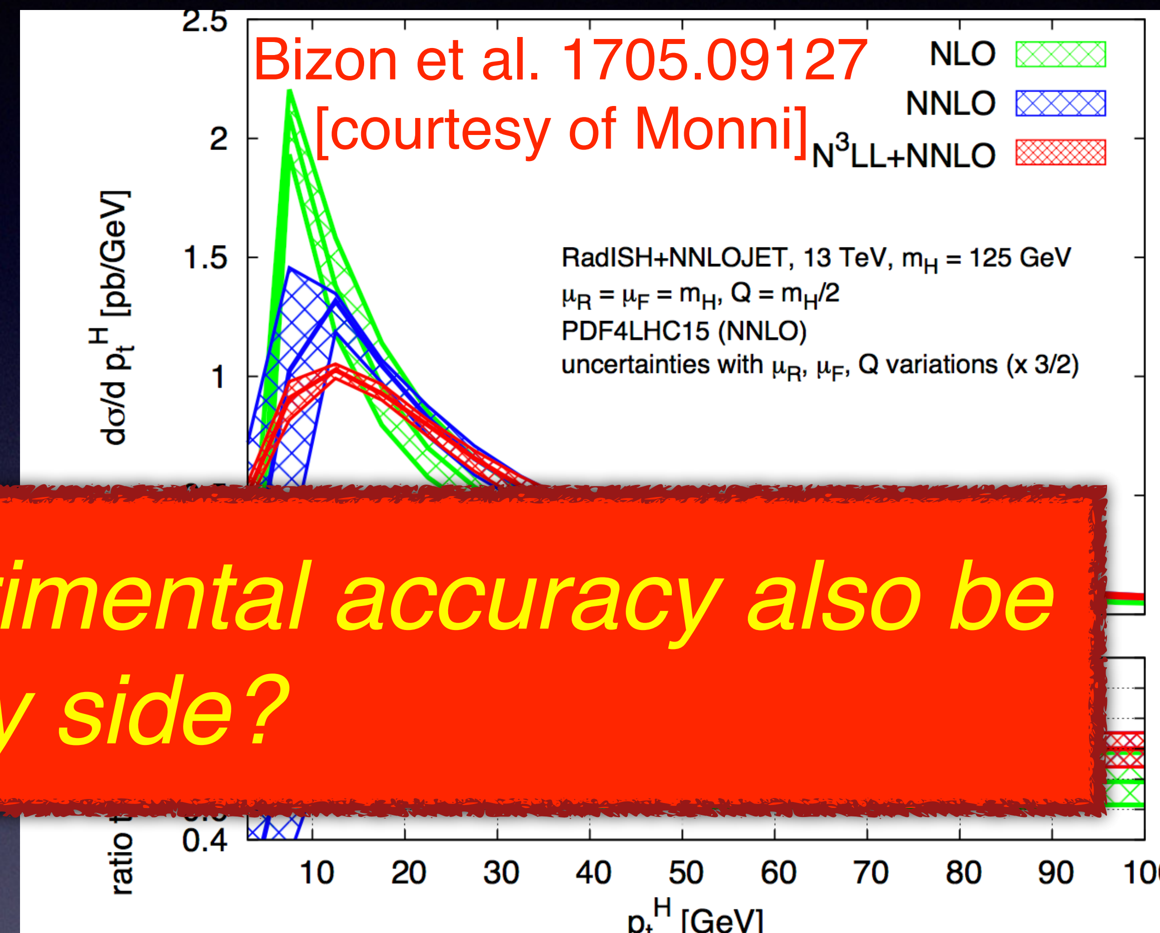


- Theory description at low-pt better than projections
- At high pt, theory description is still only leading order (loop induced). Theory improvements crucial.

See talk by Hamilton

Projections for Higgs p_t





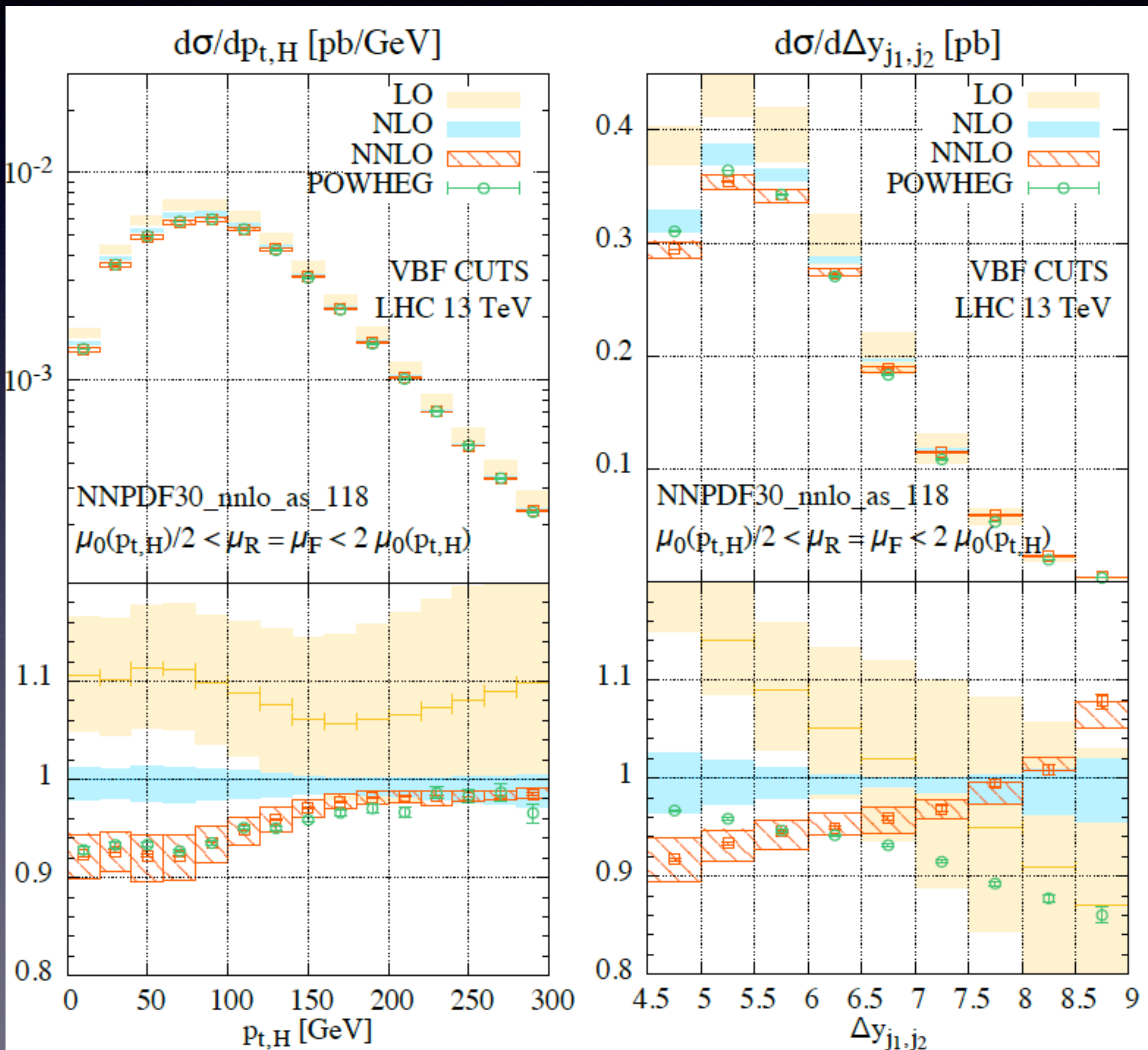
Can the projected experimental accuracy also be achieved from the theory side?

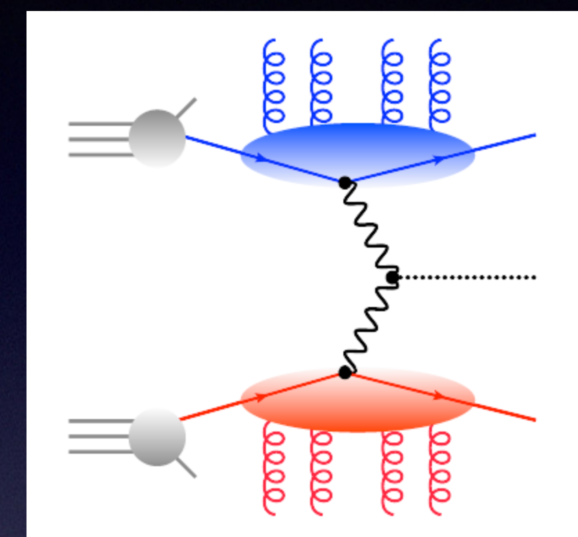
- Theory description at low-pt better than projections
- At high pt, theory description is still only leading order (loop induced). Theory improvements crucial.

See talk by Hamilton

Fully differential VBFH at NNLO

Cacciari, Dreyer, Karlberg, Salam, GZ 1506.02660

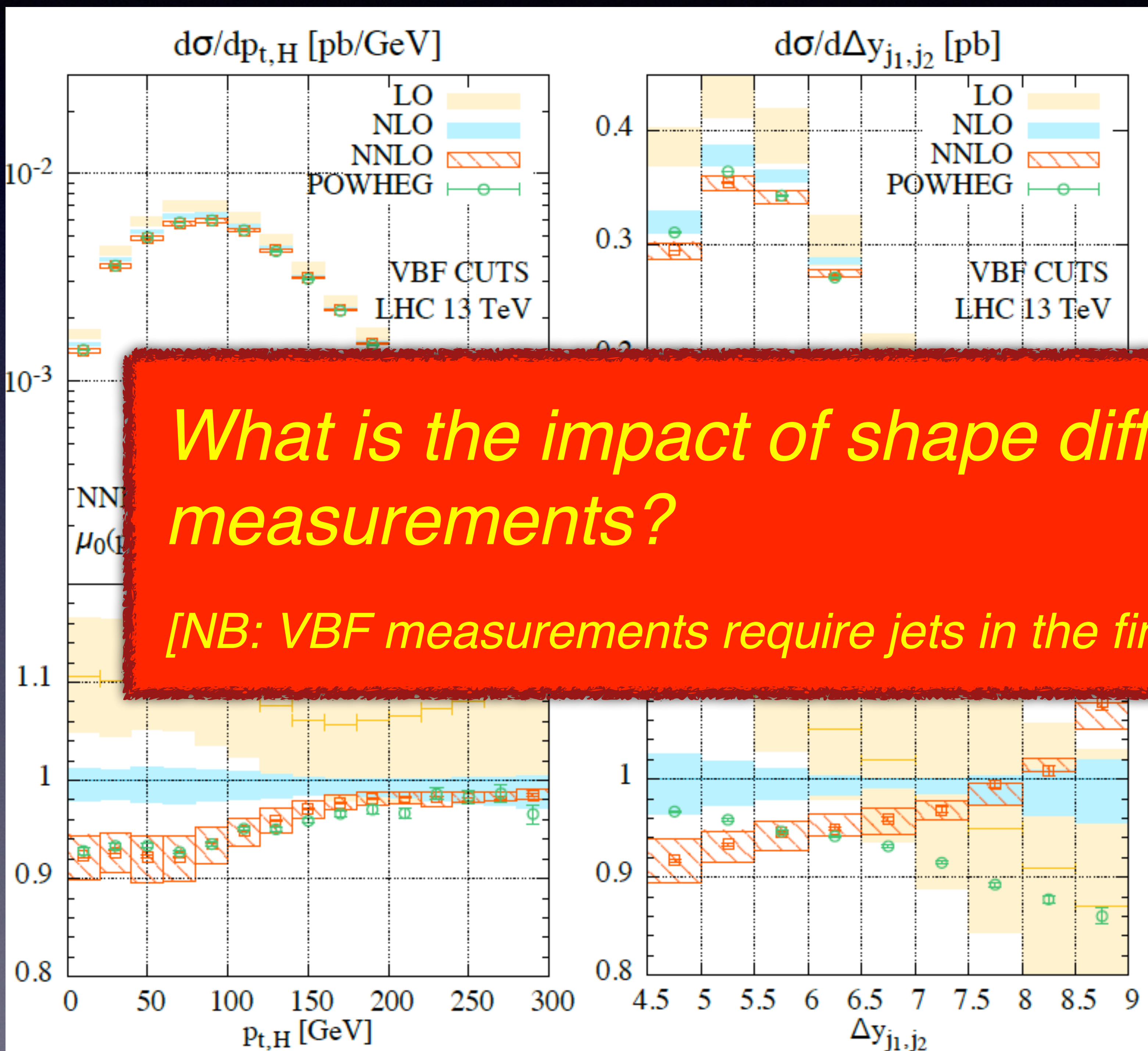


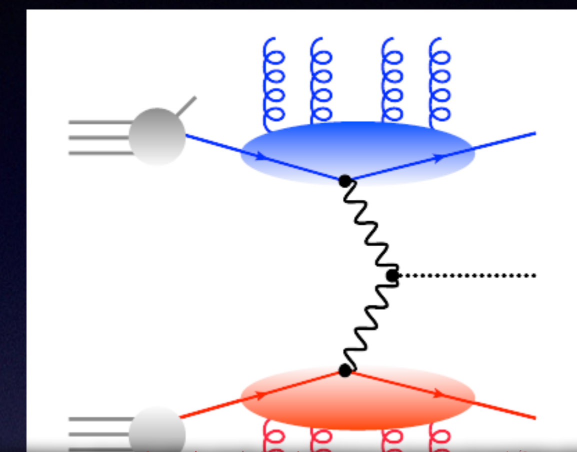


- Allows to study realistic observables, with realistic cuts
- NNLO corrections much larger (10%) than expected (1%)
- Important for coupling measurements

Fully differential VBFH at NNLO

Cacciari, Dreyer, Karlberg, Salam, GZ 1506.02660





What is the impact of shape differences on VBF measurements?

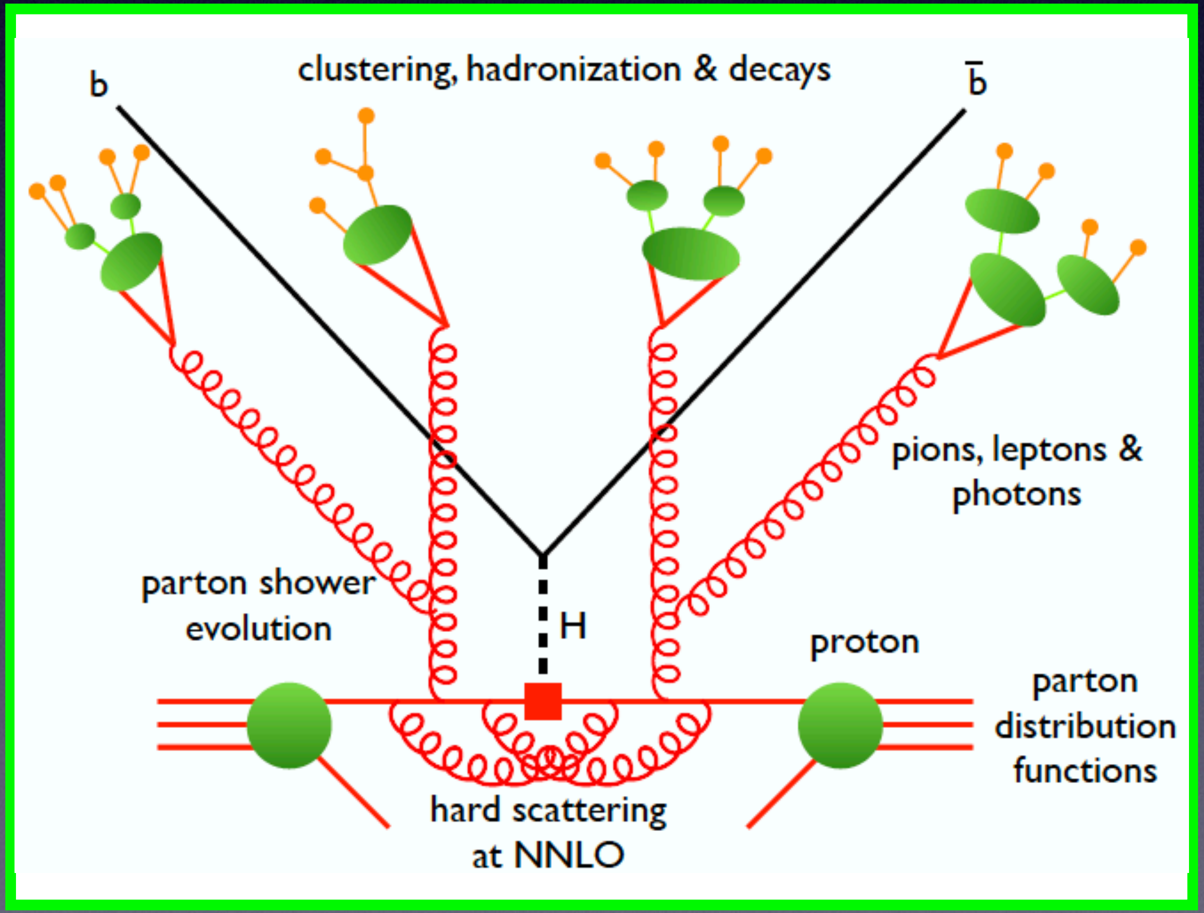
[NB: VBF measurements require jets in the final state]

listic

- NNLO corrections much larger (10%) than expected (1%)
- Important for coupling measurements

NNLO+PS

Merging NNLO and parton shower (NNLOPS) is a must to have the best perturbative accuracy with a realistic description of final state



- currently, three different methods: MiNLO, UNNLOPS, Geneva
- First NNLOPS codes: Higgs, Drell-Yan & associated Higgs production
- No NNLOPS for more complicated processes

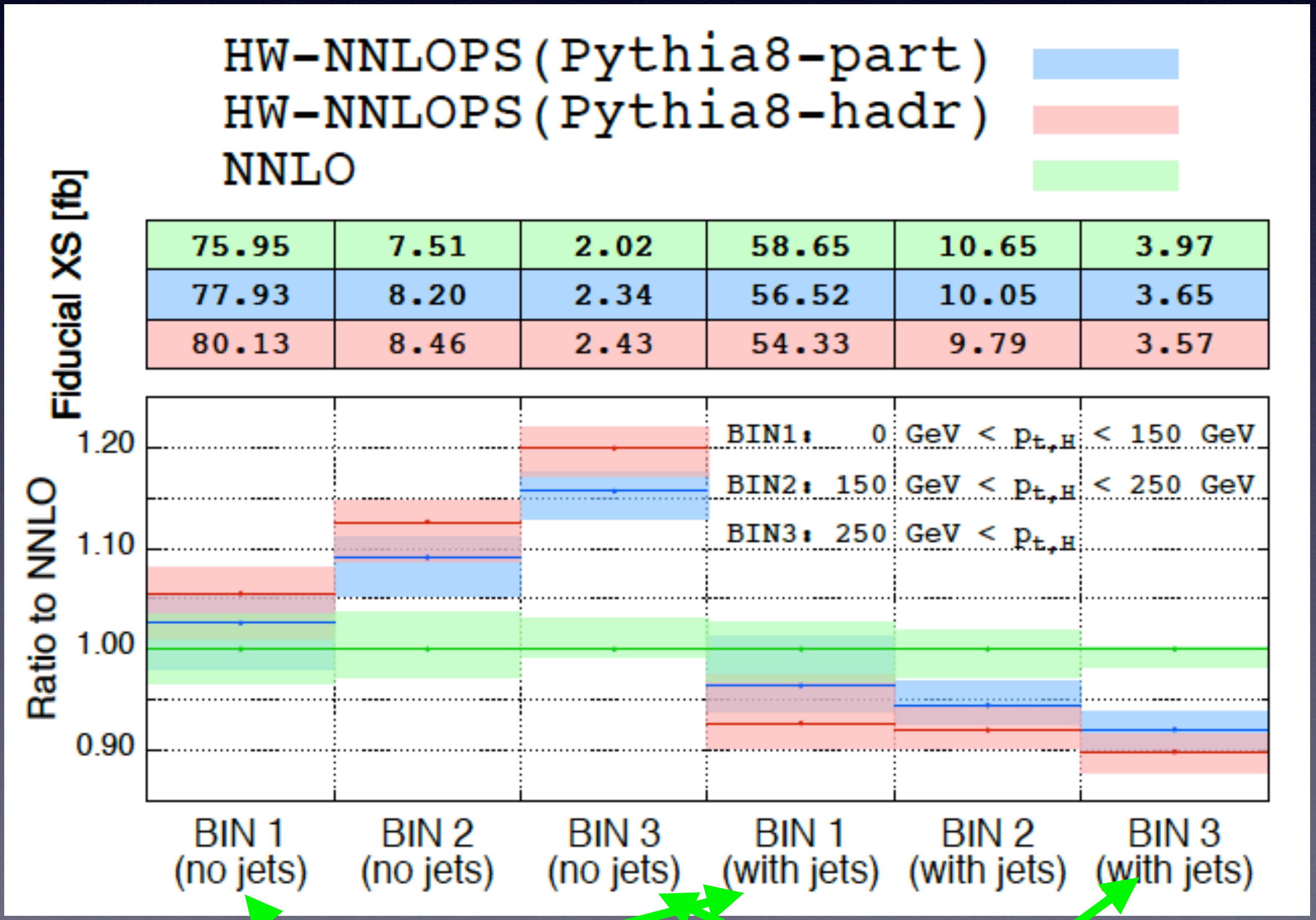
Hoeche, Li,Prestel '14-'15 [UNNLOPS]
Astill, Bizon, Hamilton, Karlberg, Nason, Re, GZ '13-'16 [MiNLO]
Alioli, Bauer, Berggren, Guns, Tackmann, Walsh '15-'16 [Geneva]

NNLO+PS for HW

One sample NNLOPS result: associated HW production with cuts suggested by HXSWG

Astill, Bizon, Re, GZ 1603.01620

- Parton shower and hadronization cause migration between jet-bins
- NNLOPS outside NNLO uncertainty band
- Difficult to reach high accuracy in jet-binned observables (used in most analysis)



Low p_t

Boosted

NNLO+PS for HW

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Astill, Bizon, Re, GZ 1603.01620

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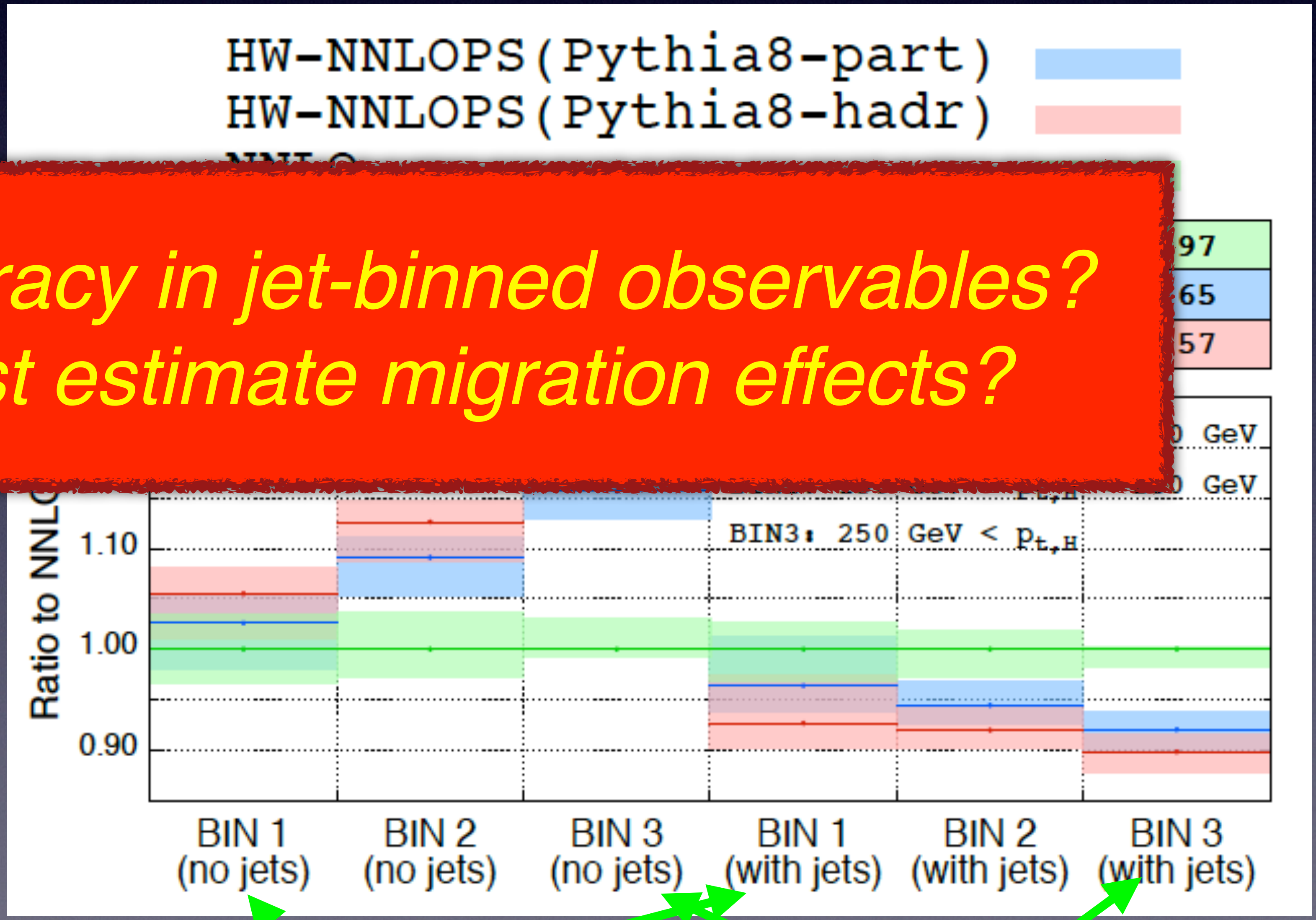


What is the accuracy in jet-binned observables?
How can one best estimate migration effects?

Low p_t

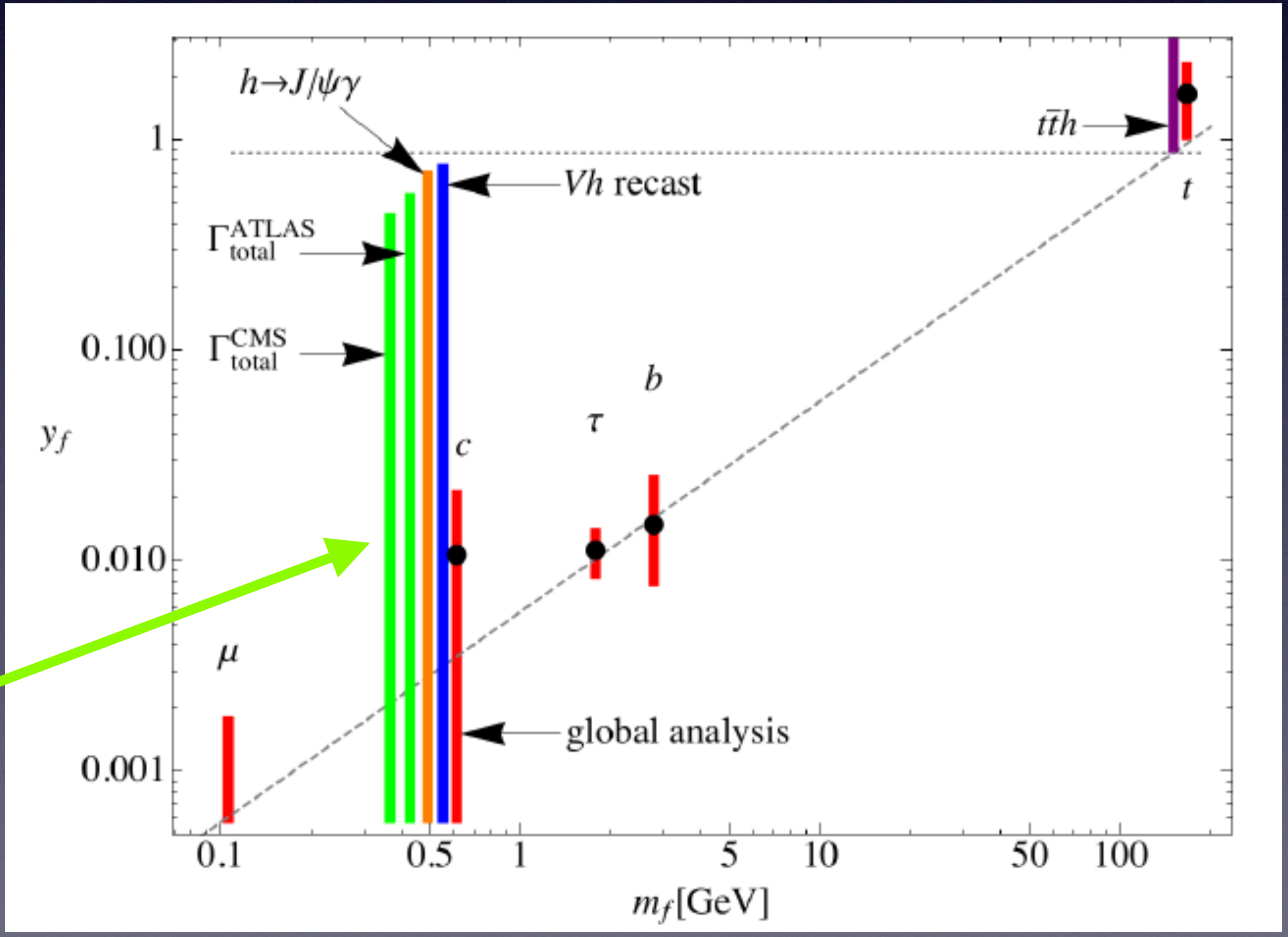
Boosted

One example where precision brings in new opportunities

Higgs coupling to 2nd generation

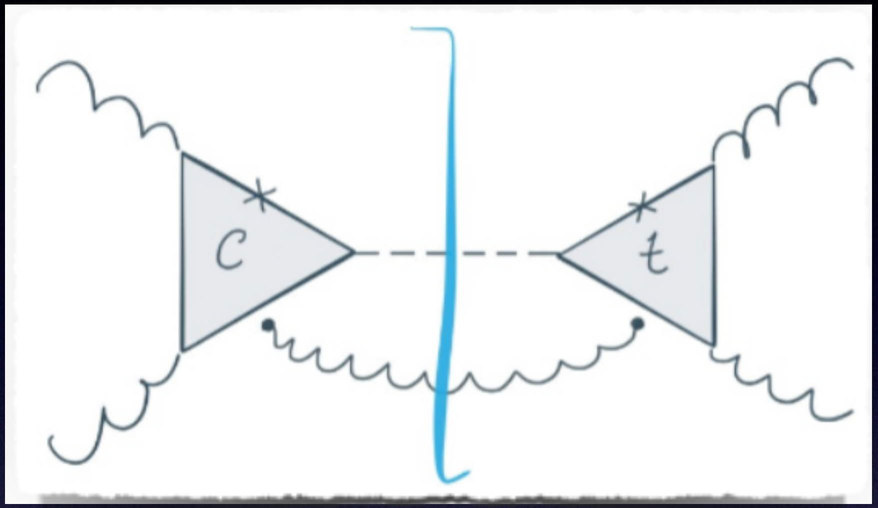
- couplings to 2nd (and 1st) generation notoriously very difficult
- a number of ways to constraint the coupling of Higgs to charm:
  - rare exclusive Higgs decays
  - Higgs + charm production
  - constraint from VH (H →bb) including charm mis-tagging
  - constraint from Higgs width

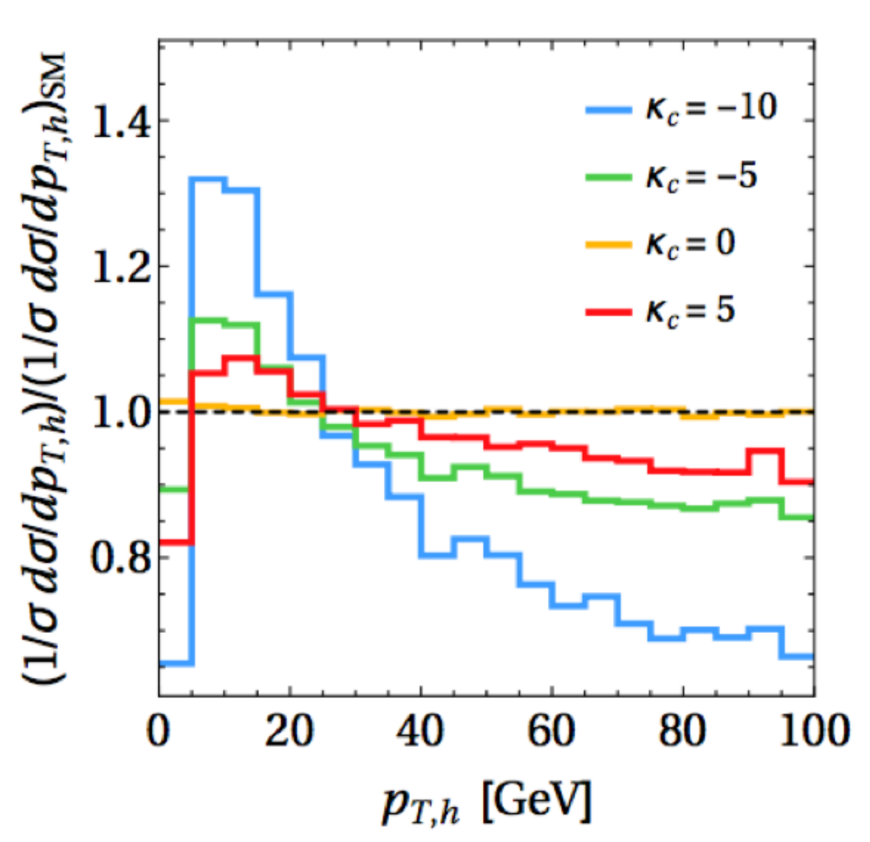
still largely unconstraint



Higgs coupling to 2nd generation

- Higgs produced dominantly via top-quark loop (largest coupling)
- but interference effects with light quarks are not negligible
- provided theoretical predictions are accurate enough (few%?), constraint on charm (and possible strange) Yukawa can be significantly improved





Bishara, Haisch, Monni, Re '16
similar ideas in Soreq, Zhu, Zupan '16

similar sensitivity in leading jet p_t

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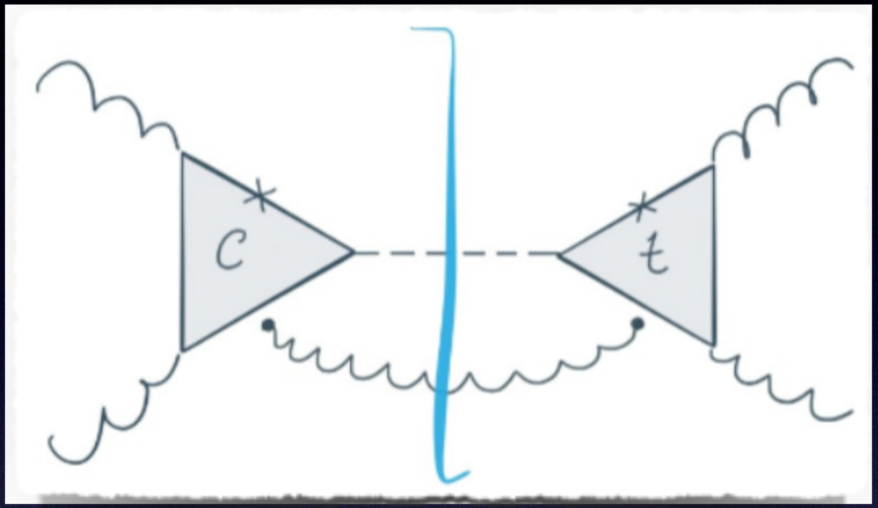

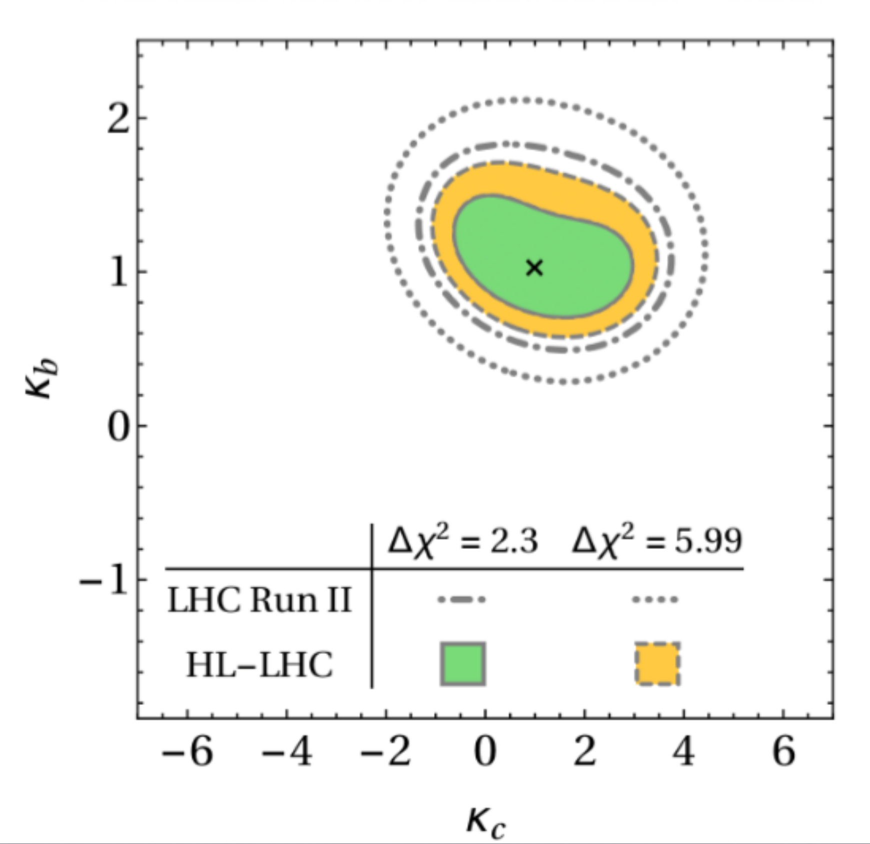

Bishara, Haisch, Monni, Re '16
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See talk by Bishara

Higgs coupling to 2nd generation

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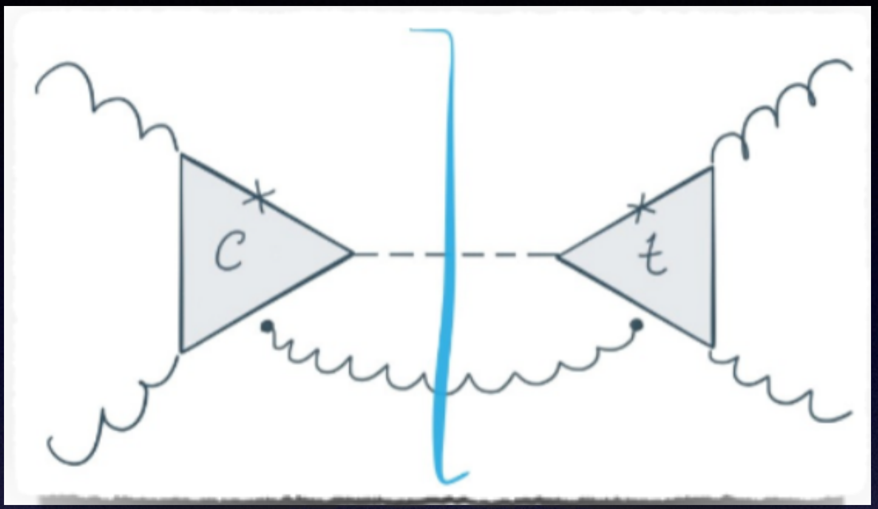
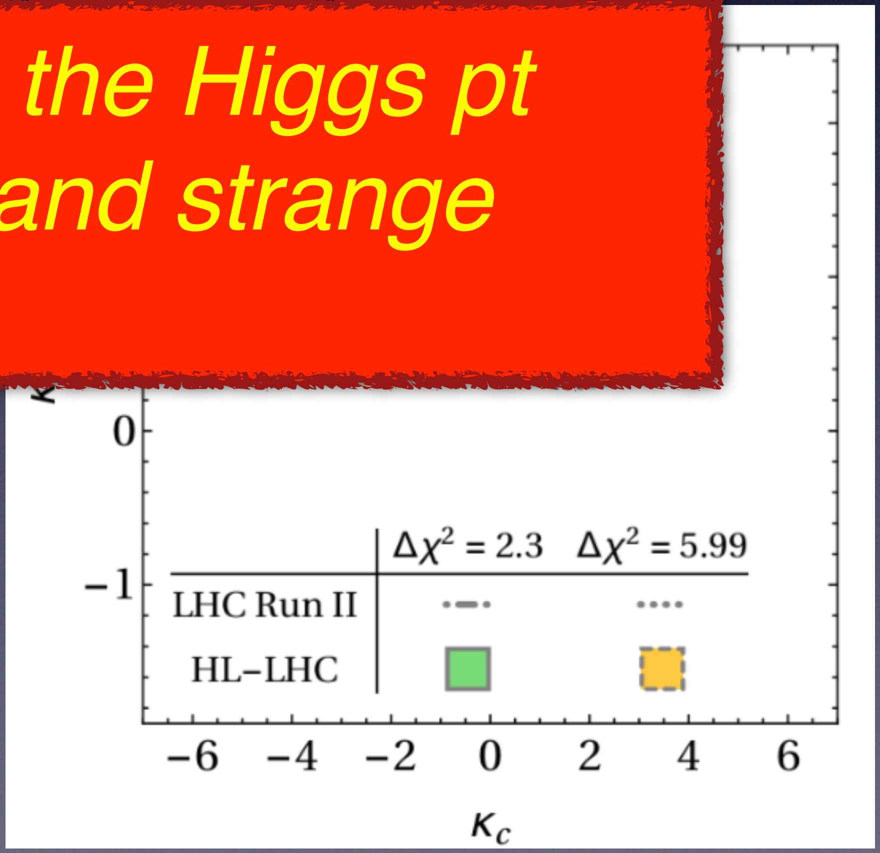
What is the accuracy required on the Higgs pt spectrum to constrain the charm and strange Yukawa?





Bishara, Haisch, Monni, Re ’16
similar ideas in Soreq, Zhu, Zupan ’16

See talk by Bishara

A few phenonenological questions/studies for the HL/HE-program:

- Do we need to revise the procedure to assign theory uncertainties?
- In which cases can the projected experimental precision be achieved from the theory side with current know-how? When not, what is required on the theory side?
- Given NNLO and NLO EW, what is the total theory uncertainty (in e.g. V+jet, VV, …)? At which point could the tension between data and theory be interpreted as a sign of a significant deviation from the SM?
- What is the accuracy in jet-binned observables? How can one best estimate migration effects? [ST method, JVE method …]
- What is the accuracy required on the Higgs p_t spectrum to constrain the charm and strange Yukawa?
- …

Technical challenges for the HL/HE-program:

- NNLO $2 \rightarrow 3$ processes, e.g.
  - Production of 3 vector bosons (VVV) [quartic couplings]
  - Higgs plus di-jet production [background to VBF Higgs production]
  - VBF W/Z production
  - Productions of 3 jets [strong coupling, PDFs, …]
- Internal masses
  - Higgs at large transverse momentum, currently described only at LO accuracy
  - Mixed QCD+EW corrections (short term: assess ambiguity in how they are combined; long term: compute genuine mixed corrections)
- NNLO production and decay, e.g.
  - NNLO top production and decay
- Off-shell effects/interferences
- Merging of NNLO to parton showers for complicated processes
- Improve logarithmic accuracy of parton showers