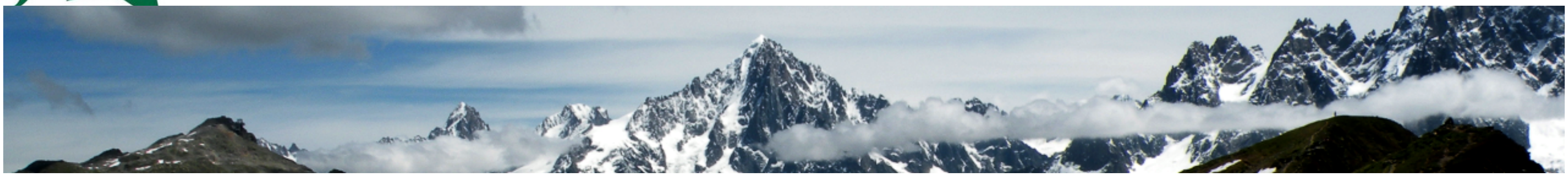
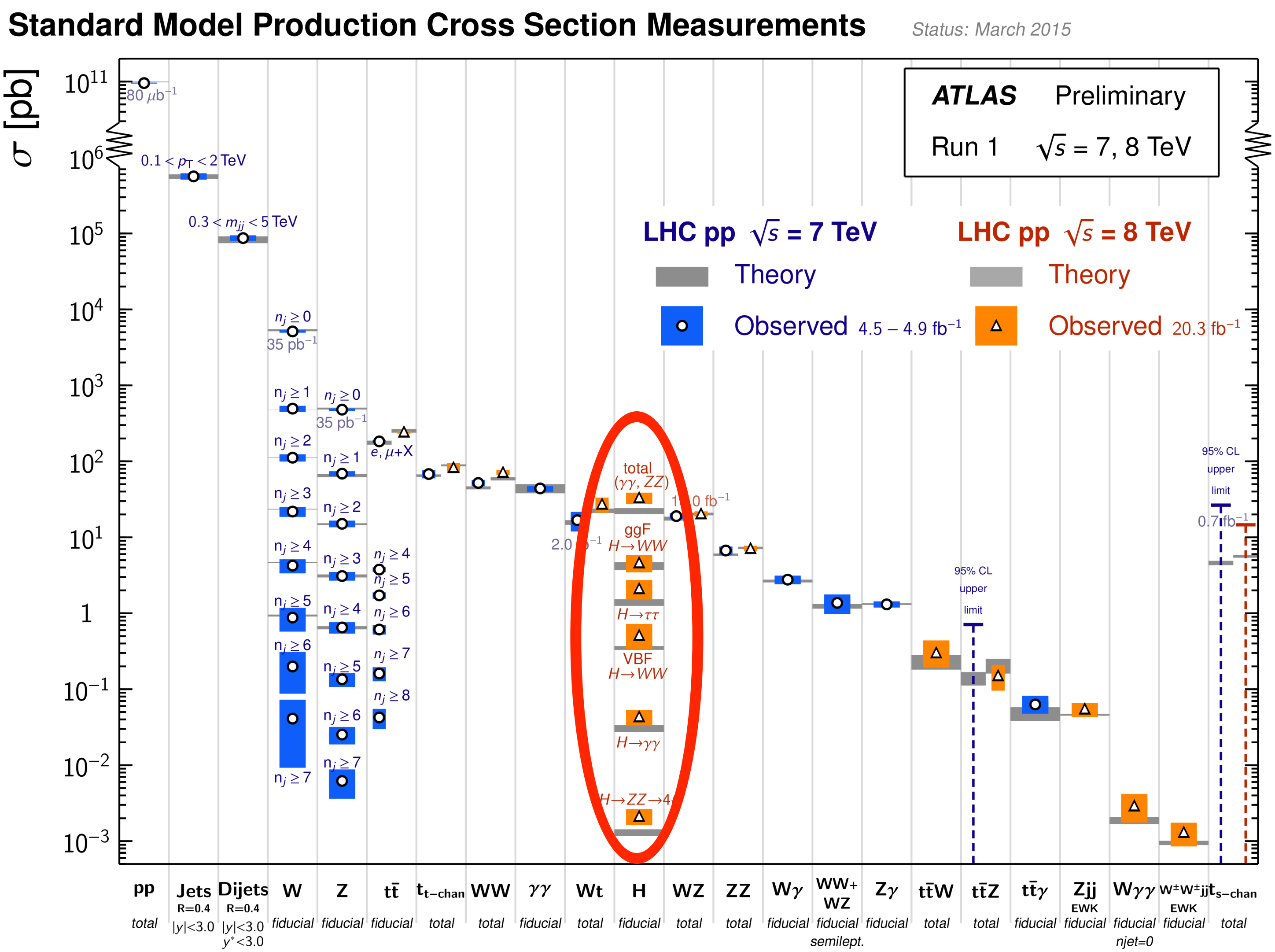


NLM Working Group Intro …from an experimentalist perspective

J. Huston

Michigan State University/IPPP

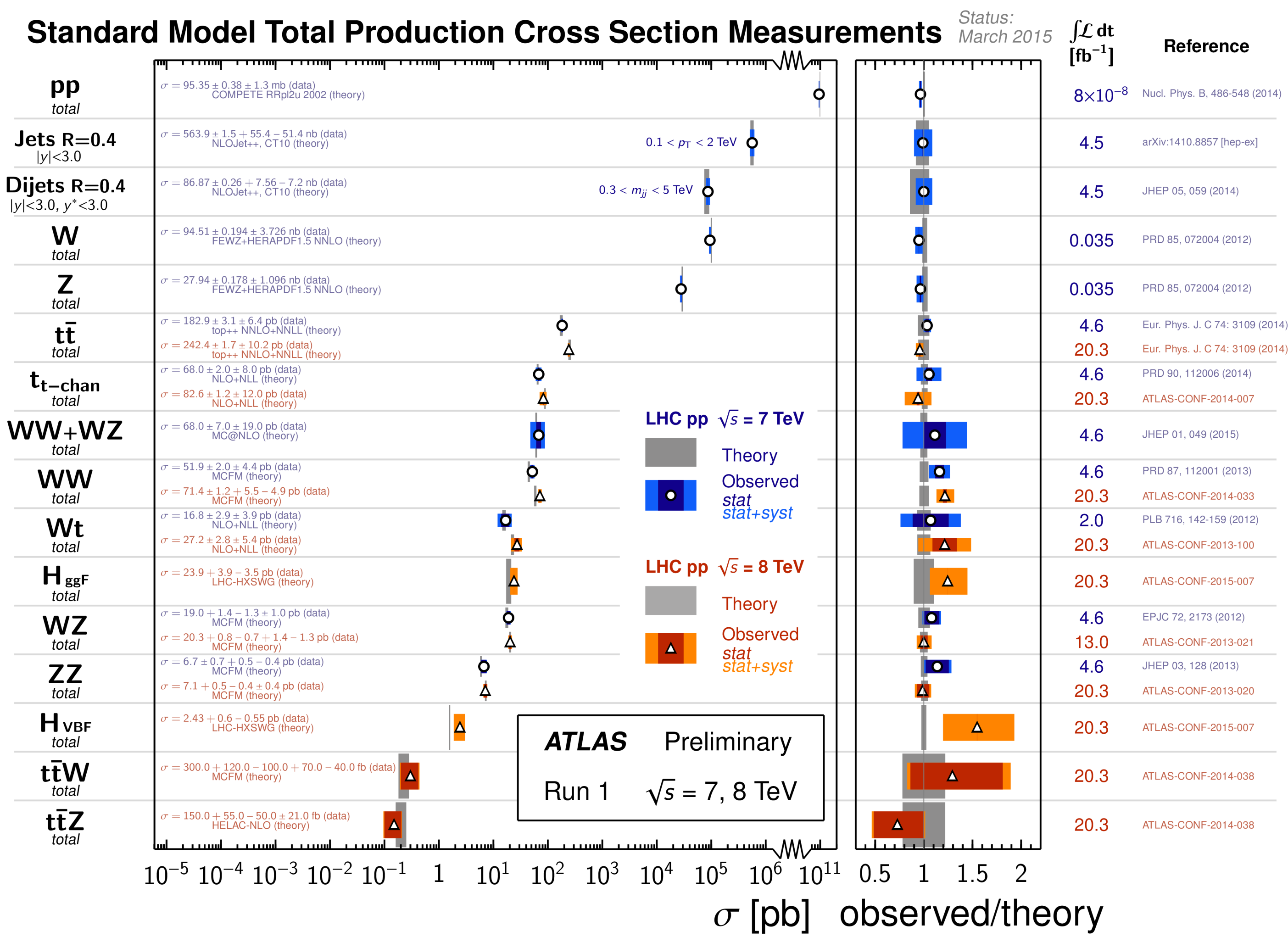
Re-discovery of the standard model in Run 1



+similar for CMS of course

Physics from Run 1

…in most cases, good agreement with SM predictions (at NLO and higher). The SM will be tested more stringently (with hopefully BSM physics discovered) in Run 2. We need to have the predictions available to test data vs theory.



A new Les Houches high precision wishlist

- From the 2013 proceedings
  - arxiv:1405.1067
- NB: The counting of orders is done relative to LO QCD independent of the absolute power of α_s in cross section
- $\alpha \sim \alpha_s^2$ so that NNLO QCD and NLO EW effects are naively of the same size
- $d\sigma$ represents full differential cross sections
- The list is very ambitious, but possible to do over the remainder of the LHC running
- Looking forward to the discussions of jettiness

– $\mathrm{LO} \equiv \mathcal{O}(1)$,

– $\mathrm{NLO\ QCD} \equiv \mathcal{O}(\alpha_s)$,

– $\mathrm{NNLO\ QCD} \equiv \mathcal{O}(\alpha_s^2)$,

– $\mathrm{NLO\ EW} \equiv \mathcal{O}(\alpha)$,

– $\mathrm{NNNLO\ QCD} \equiv \mathcal{O}(\alpha_s^3)$,

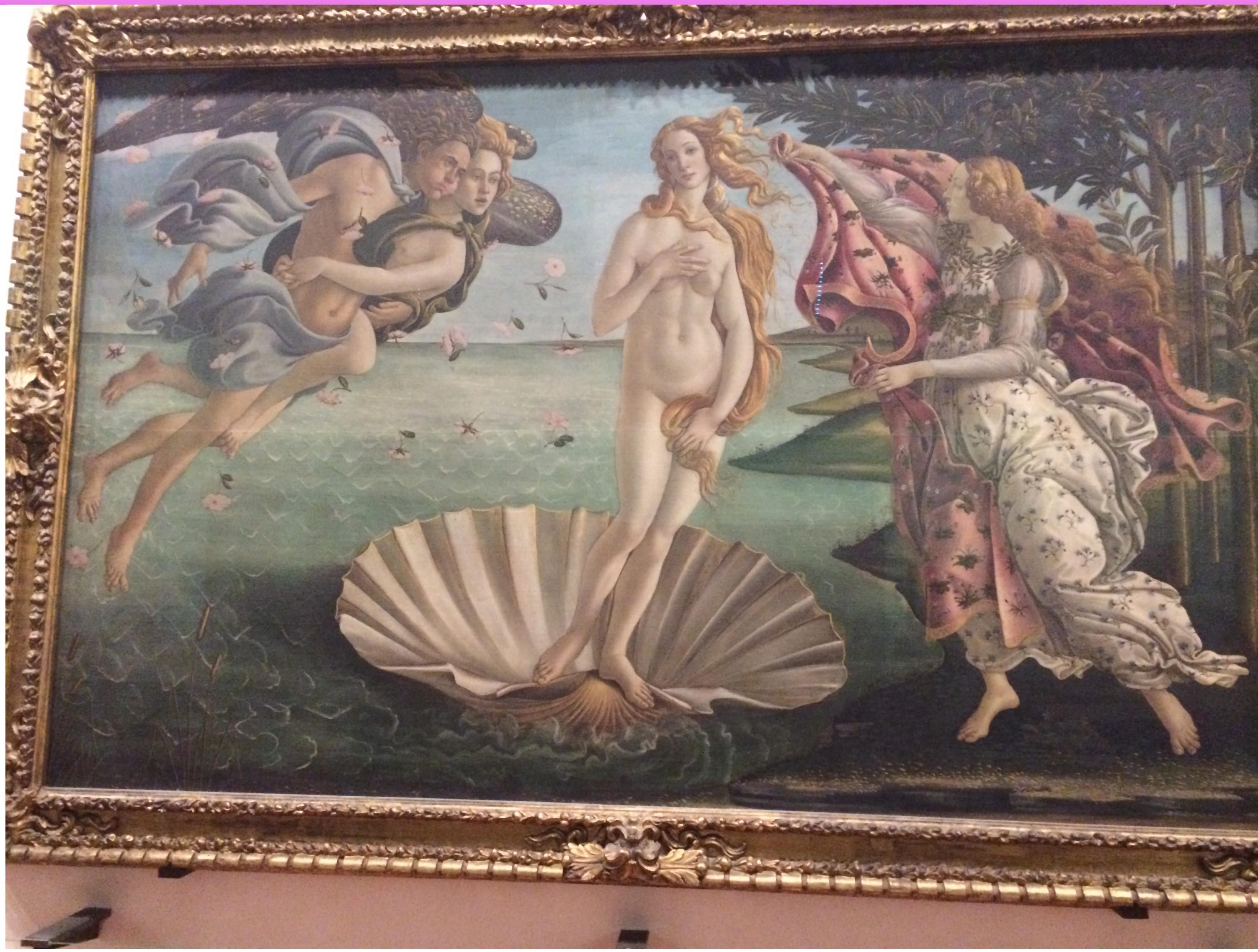
– $\mathrm{NNLO\ QCD{+}EW} \equiv \mathcal{O}(\alpha_s \alpha)$.

…and of course, as much as possible, we would like matching to a parton shower for fully exclusive final states

Costas: “δεν υπάρχει πρόβλημα”

In this notation, $d\sigma$@NNLO QCD+NLO EW indicates a single code computing the fully differential cross section including both order α_s^2 and order α effects. Where possible, full resonance production, including interference with background should be taken into account.

Many of these calculations require the use of on-shell techniques



…which have been around longer than we realized

Wishlist: Higgs sector

Process	known	desired	details
H	dσ @ NNLO QCD dσ @ NLO EW finite quark mass effects @ NLO	dσ @ NNNLO QCD + NLO EW MC@NNLO finite quark mass effects @ NNLO	H branching ratios and couplings
H + j	dσ @ NNLO QCD dσ @ NLO EW finite quark mass effects @ LO	dσ @ NNLO QCD + NLO EW finite quark mass effects @ NLO	H p_T
H + 2j	σ_{tot}(VBF) @ NNLO(DIS) QCD dσ(gg) @ NLO QCD dσ(VBF) @ NLO EW	dσ @ NNLO QCD + NLO EW	H couplings
H + V	dσ @ NNLO QCD dσ @ NLO EW	with $H \to \mathrm{b\bar{b}}$ @ same accuracy	H couplings
$\mathrm{t\bar{t}H}$	dσ(stable tops) @ NLO QCD	dσ(top decays) @ NLO QCD + NLO EW	top Yukawa coupling
HH	dσ @ LO QCD (full m_t dependence) dσ @ NLO QCD (infinite m_t limit)	dσ @ NLO QCD (full m_t dependence) dσ @ NNLO QCD (infinite m_t limit)	Higgs self coupling

Table 1: Wishlist part 1 – Higgs (V = W, Z)

→ justify the requested precision based on current/extrapolated experimental errors

S. Dittmaier, N. Glover, J. Huston

Higgs sector

- We currently know the production cross section for gg fusion to NNNLO QCD in the infinite m_t limit, including finite quark mass effects at NLO QCD and NLO EW.
- Current experimental uncertainties are of the order of 20-40%

Process	known	desired	details
H	dσ @ NNLO QCD dσ @ NLO EW finite quark mass effects @ NLO	dσ @ NNNLO QCD + NLO EW MC@NNLO finite quark mass effects @ NNLO	H branching ratios and couplings

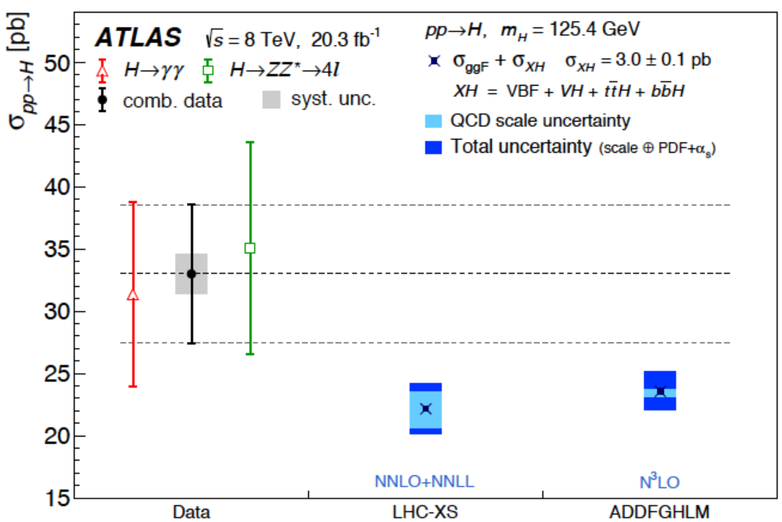
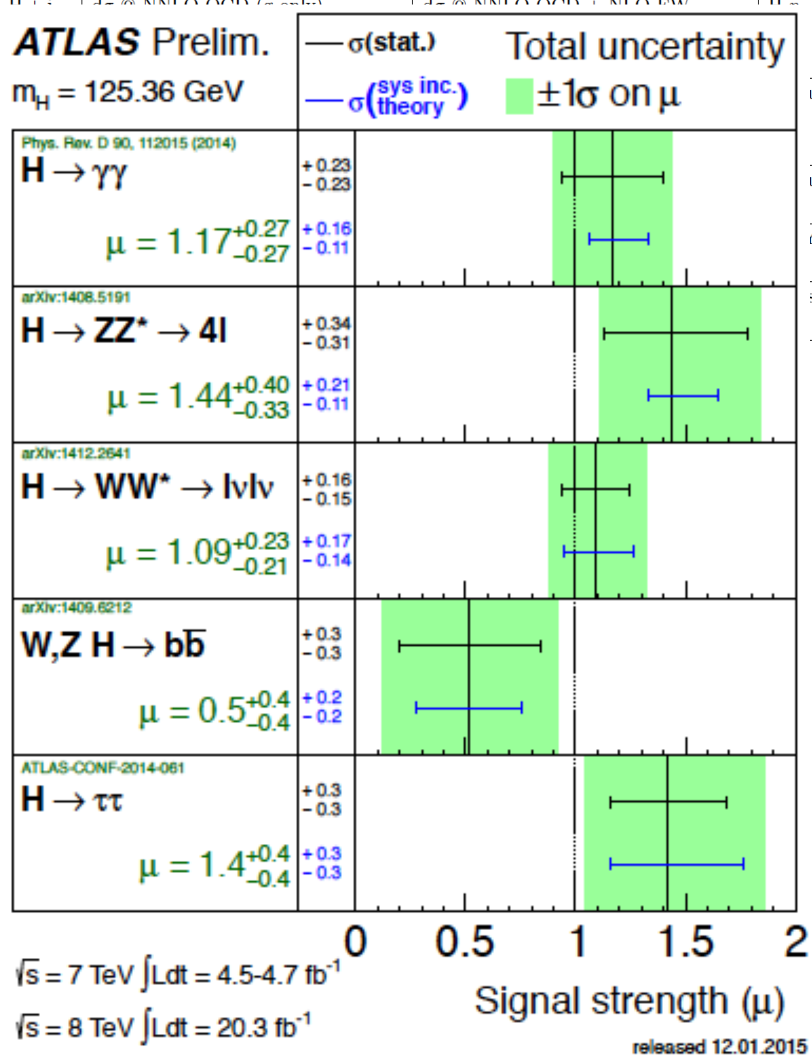


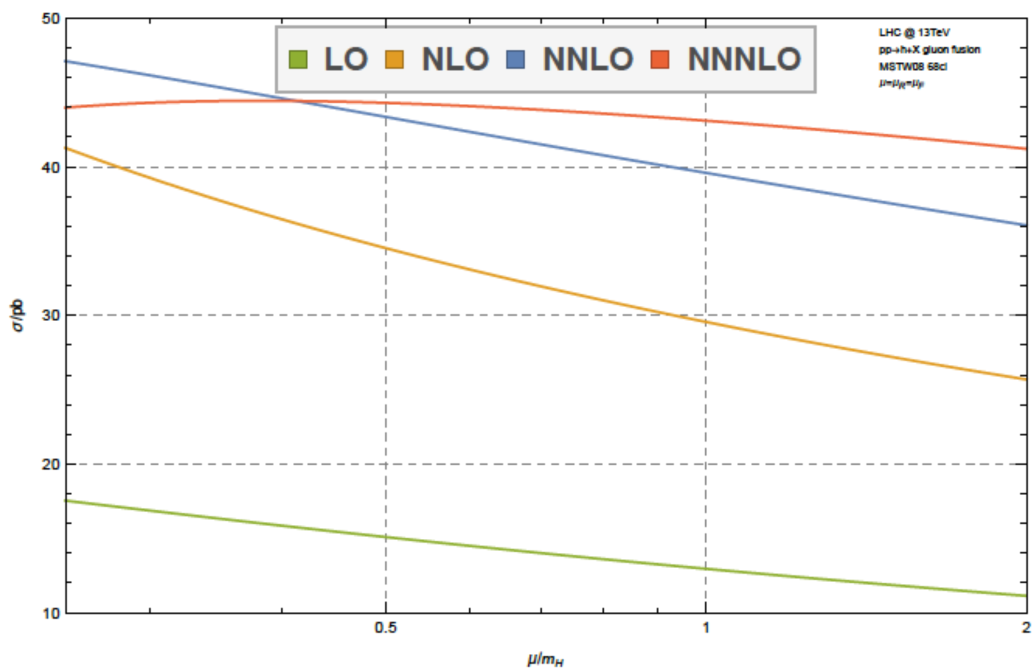
FIG. 1. Measured total cross section of Higgs boson production compared to two calculations of the ggF cross section. Contributions from other relevant Higgs boson production modes (VBF, VH, $t\bar{t}H$, $b\bar{b}H$) are added using cross sections and uncertainties from Ref. [10]. Details of the predictions are presented in Table I.



Higgs sector

- We currently know the production cross section for gg fusion to NNNLO QCD in the infinite m_t limit, including finite quark mass effects at NLO QCD and NLO EW.
- Small corrections NNLO to NNNLO
  - scale uncertainties no longer dominant? ->now PDF+α_s uncertainties (7-8%) dominant? (see later)
  - **does this calculation provide lessons for resummation calculations?**
- Expect total experimental error to decrease to 10% in Run 2
- So ultimately may want to know NNNLO QCD and mixed NNLO QCD +EW contributions maintaining finite top quark mass effects

Process	known	desired	details
H	dσ @ NNLO QCD dσ @ NLO EW finite quark mass effects @ NLO	dσ @ NNNLO QCD + NLO EW MC@NNLO finite quark mass effects @ NNLO	H branching ratios and couplings
H + j	dσ @ NNLO QCD (g only) dσ @ NLO EW finite quark mass effects @ LO	dσ @ NNLO QCD + NLO EW finite quark mass effects @ NLO	H p_T
H + 2j	σ_{tot}(VBF) @ NNLO(DIS) QCD dσ(gg) @ NLO QCD dσ(VBF) @ NLO EW	dσ @ NNLO QCD + NLO EW	H couplings
H + V	dσ @ NNLO QCD dσ @ NLO EW	with $H \to b\bar{b}$ @ same accuracy	H couplings

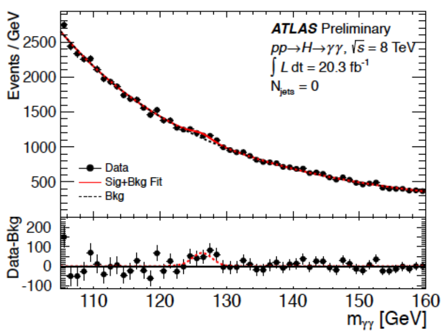


2 NNLO+PS simulations for ggF have already been developed; expect improvements/refinements.

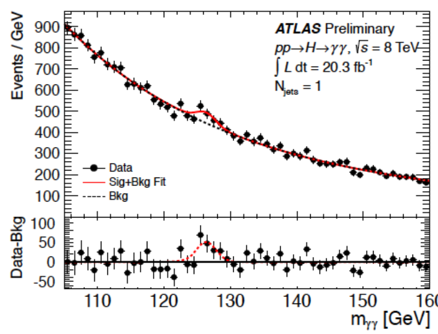
Higgs sector

- First attempts to measure differential Higgs+jets measurements made in diphoton channel at ATLAS
  - arXiv:1407.4222
- Combination with ZZ*
  - arXiv:1504.05833

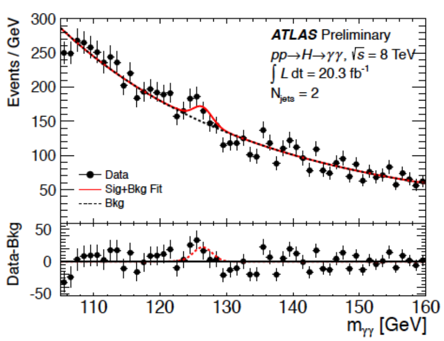
Process	known	desired	details
H	dσ @ NNLO QCD dσ @ NLO EW finite quark mass effects @ NLO	dσ @ NNNLO QCD + NLO EW MC@NNLO finite quark mass effects @ NNLO	H branching ratios and couplings
H + j	dσ @ NNLO QCD (g only) dσ @ NLO EW finite quark mass effects @ LO	dσ @ NNLO QCD + NLO EW finite quark mass effects @ NLO	H p_T



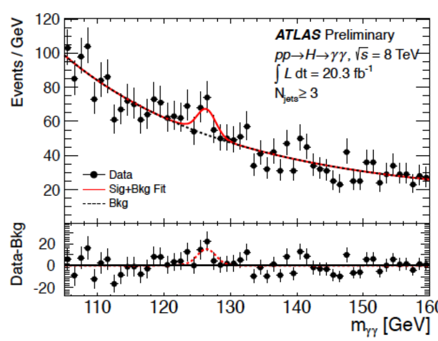
(a) $N_{\text{jets}} = 0$



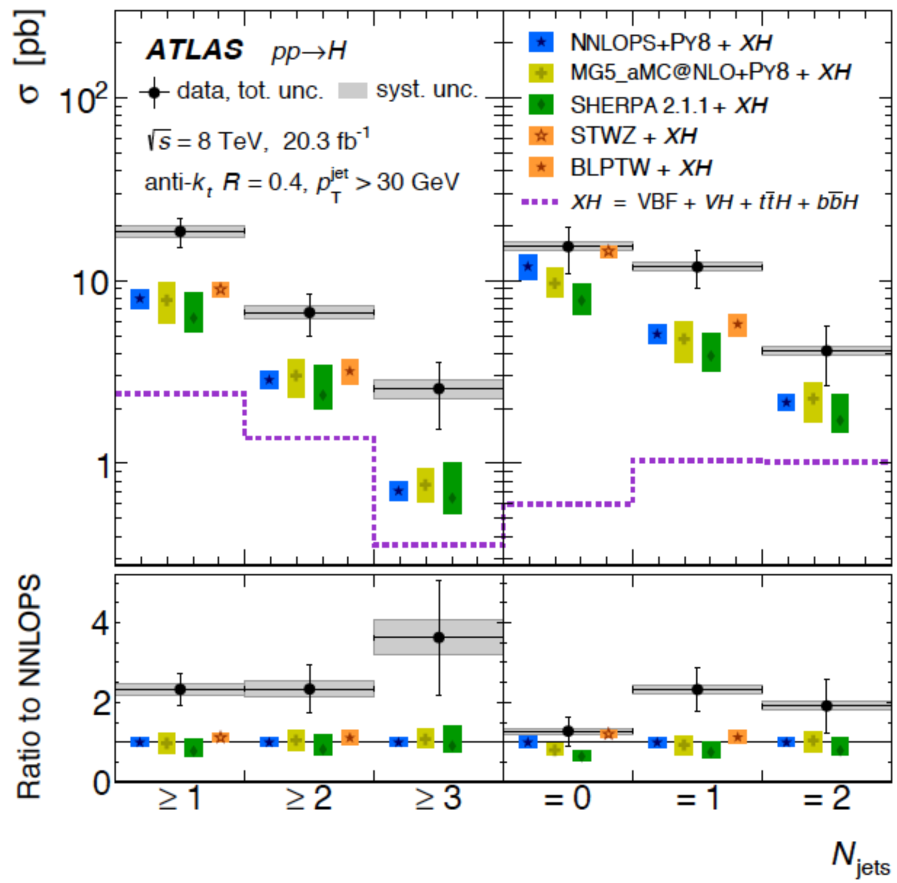
(b) $N_{\text{jets}} = 1$



(c) $N_{\text{jets}} = 2$

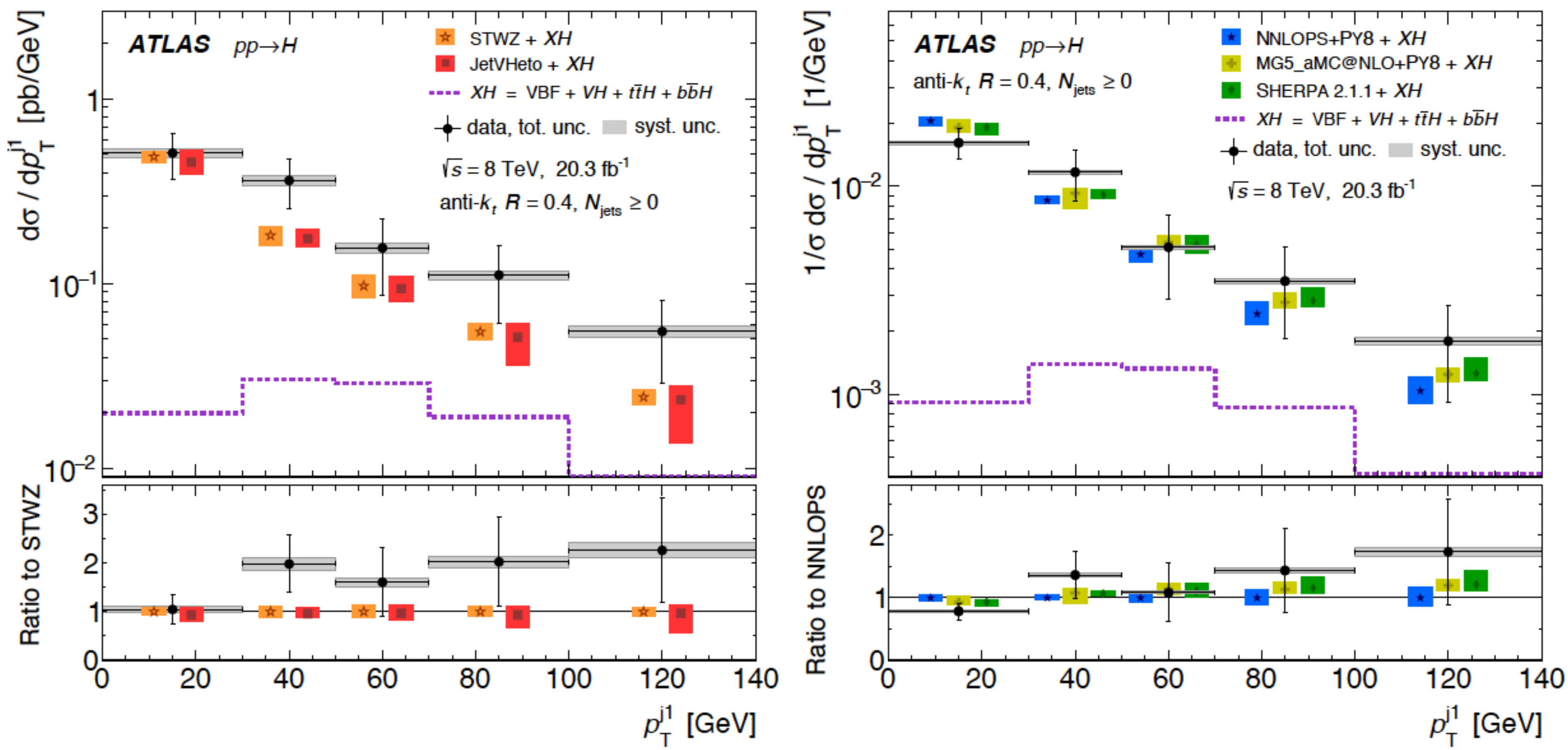


(d) $N_{\text{jets}} \geq 3$



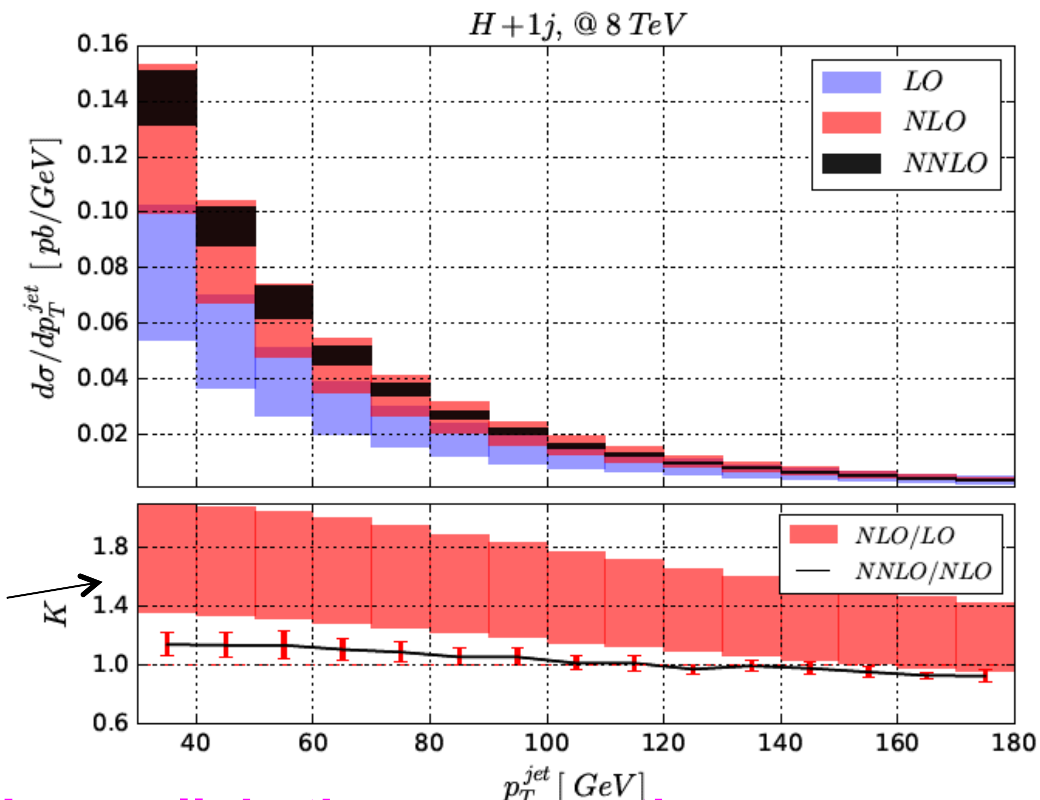
ATLAS Higgs+>=1 jet

- Comparisons to a wide number of resummation/ ME+PS predictions…**but not to fixed order**!



Higgs + jet

- At 14 TeV, with 300 fb^{-1}, there will be a rich variety of differential jet measurements with on the order of 3000 events with jet p_T above the top quark mass scale, thus probing inside the top quark loop
- H+j cross section now known to NNLO
  - using *conventional* techniques: arXiv:1504.07922
  - using jettiness: arXiv:1505.03893
- LO (one-loop) QCD and EW corrections with top mass dependence known, but finite mass contributions at NNLO QCD+NLO EW may also be needed



How well do the resummation (exponentiation?) calculations anticipate the NNLO corrections for Higgs+>=1 jet? Do they show the corrections decreasing as a function of jet p_T in the same way? ->Les Houches exercise

F. Caola: HXSWG meeting May 7, 2015

LHC13 efficiencies: 0- and 1-jet bin

[Many thanks to P. F. Monni and F. Dulat]

0-jet bin

ord	$\sigma^{\rm f.o.}_{0-\rm jet}$ (JVE)	$\sigma^{\rm f.o.+NNLL}_{0-\rm jet}$ (JVE)	$\sigma^{\rm f.o.+NNLL}_{0-\rm jet}$ (scales)
NNLO	$26.2^{+4.0}_{-4.0}$ pb	$25.8^{+3.8}_{-3.8}$	$25.8^{+1.6}_{-1.6}$
$\rm N^3LO$	$27.2^{+2.7}_{-2.7}$ pb	$27.2^{+1.4}_{-1.4}$	$27.2^{+0.9}_{-0.9}$

≥1-jet bin

ord	$\sigma^{\rm f.o.}_{\geq 1-\rm jet}$ (scales)	$\sigma^{\rm f.o.}_{\geq 1-\rm jet}$ (JVE)	$\sigma^{\rm f.o.+NNLL}_{\geq 1-\rm jet}$ (JVE)
NLO	$14.7^{+2.8}_{-2.8}$ pb	$14.7^{+3.4}_{-3.4}$	$15.1^{+2.7}_{-2.7}$
NNLO	$17.5^{+1.3}_{-1.3}$ pb	$17.5^{+2.6}_{-2.6}$	$17.5^{+1.1}_{-1.1}$

- Logs completely under control
  (logR: see [Dasgupta, Dreyer, Salam, Soyez (2015)])
- No breakdown of f.o. perturbation theory for p_T ~ 30 GeV
- Reliable error estimate from lower orders
- Logs help in reducing uncertainties
- Significant decrease of pert. uncertainty

Preliminary

What is the effect of jet binning on a reasonably inclusive cross section, i.e. H+>=1 jet?

According to this result, the effects are small.

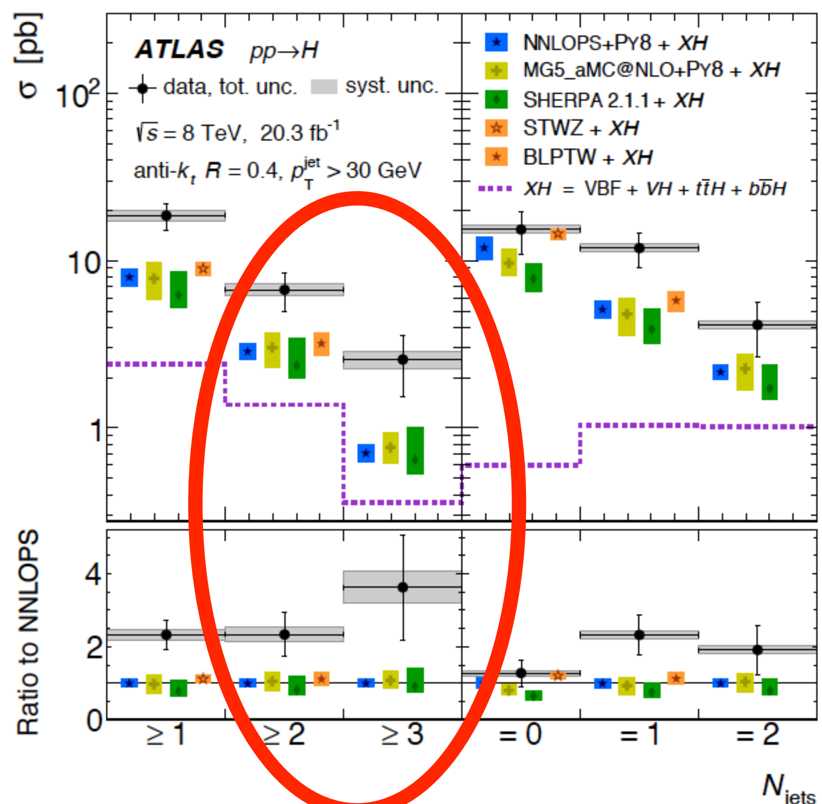
Can we (I) get a better understanding of this?

Higgs sector

- Higgs +>= 2 jets crucial to understand Higgs coupling, in particular through VBF
- VBF production known to NNLO QCD in double-DIS approximation together with QCD and EW effects at NLO, while ggF known in infinite top mass limit and to LO QCD retaining top mass effects
- With 300 fb^{-1}, there is the possibility of measuring HWW coupling strength to order of 5%
- This would require both VBF and ggF Higgs + 2 jets cross sections to NNLO QCD and finite mass effects to NLO QCD and NLO EW

Process	known	desired	details
H	$d\sigma$ @ NNLO QCD $d\sigma$ @ NLO EW finite quark mass effects @ NLO	$d\sigma$ @ NNNLO QCD + NLO EW MC@NNLO finite quark mass effects @ NNLO	H branching ratios and couplings
H + j	$d\sigma$ @ NNLO QCD (g only) $d\sigma$ @ NLO EW finite quark mass effects @ LO	$d\sigma$ @ NNLO QCD + NLO EW finite quark mass effects @ NLO	H p_T
H + 2j	σ_{tot}(VBF) @ NNLO(DIS) QCD $d\sigma$(gg) @ NLO QCD $d\sigma$(VBF) @ NLO EW	$d\sigma$ @ NNLO QCD + NLO EW	H couplings
H + V			
$t\bar{t}$H			
HH			

3



interesting that the (statistically limited) results seem to show a jettier final state than predicted

Higgs+jets study

- Higgs+jets production is one of the most interesting channels at the LHC, especially with regards to VBF measurements and to probes with accompanying high p_T jets
- Experimentalists have used a variety of predictions to compare to data, including resummed predictions and NLO ME+PS event generation
- At this Les Houches, we would like to do benchmarking with respect to fixed order predictions
  - **are the differences confined to the Sudakov regions?**
  - **how do the different implementations agree/ disagree with each other?**
- A Rivet routine was distributed to interested parties
  - please let us know if you'd also like to use it
- Comparisons will be made to predictions from gosam for Higgs +>=1,2 and 3 jets at NLO, through a ROOT ntuple interface
  - results are in the Blackhat +Sherpa ntuple format
  - histograms available from Les Houches wiki
- Comparisons to be made at the perturbative level, i.e. no underlying event or fragmentation for the ME+PS programs, as well as at the hadron level

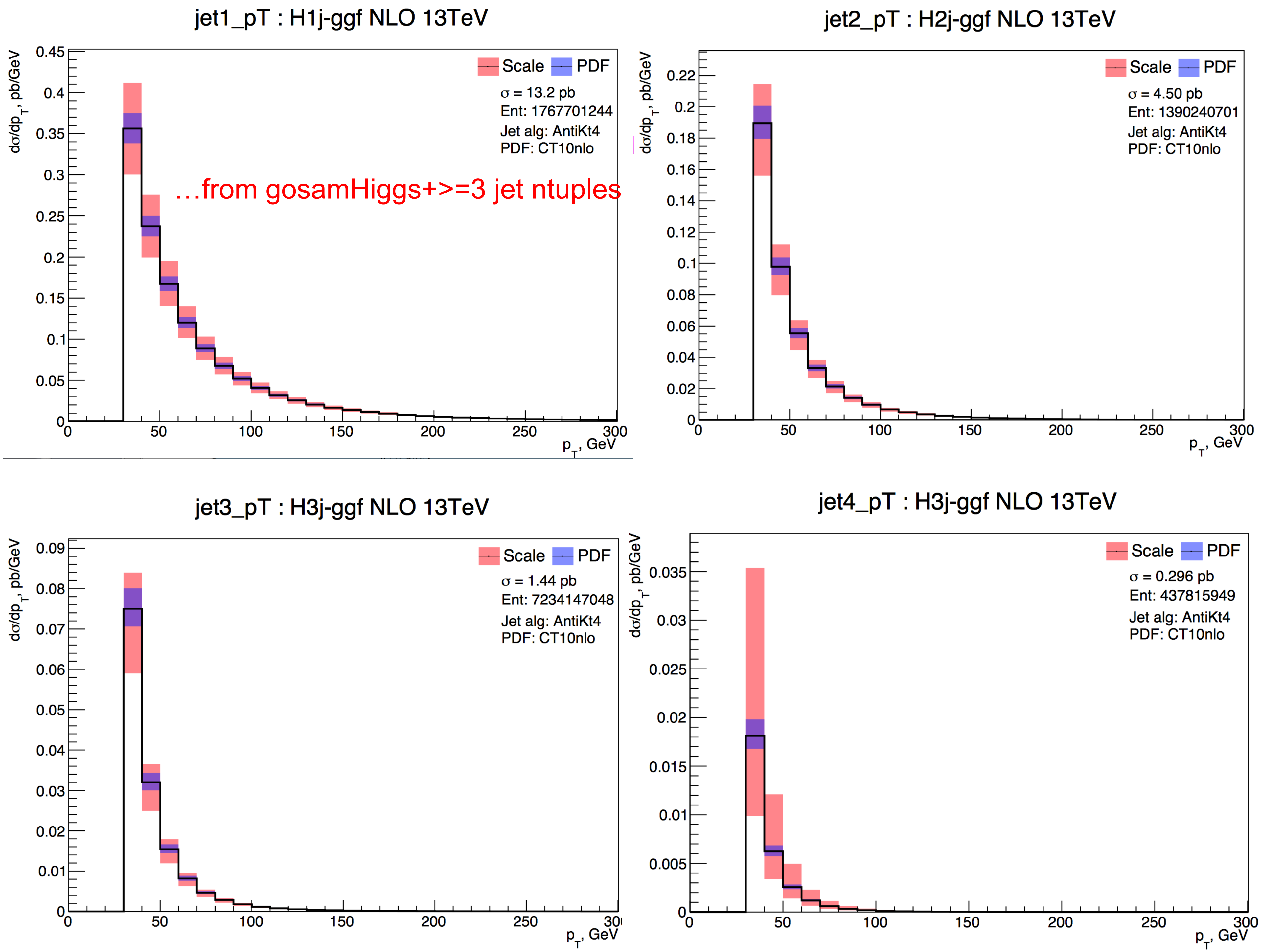
arXiv:1310.7439

branch name	type	Notes
id	I	id of the event. Real events and their associated counterterms share the same id. This allows for the correct treatment of statistical errors.
nparticle	I	number of particles in the final state
px	F[nparticle]	array of the x components of the final state particles
py	F[nparticle]	array of the y components of the final state particles
pz	F[nparticle]	array of the z components of the final state particles
E	F[nparticle]	array of the energy components of the final state particles
alphas	D	$alpha_s$ value used for this event
kf	I	PDG codes of the final state particles
weight	D	weight of the event
weight2	D	weight of the event to be used to treat the statistical errors correctly in the real part
me_wgt	D	matrix element weight, the same as weight but without pdf factors
me_wgt2	D	matrix element weight, the same as weight2 but without pdf factors
x1	D	fraction of the hadron momentum carried by the first incoming parton
x2	D	fraction of the hadron momentum carried by the second incoming parton
x1p	D	second momentum fraction used in the integrated real part
x2p	D	second momentum fraction used in the integrated real part
id1	I	PDG code of the firt incoming parton
id2	I	PDG code of the second incoming parton
fac_scale	D	factorization scale used
ren_scale	D	renormalization scale used
nuwgt	I	number of additional weights
usr_wgts	D[nuwgt]	additional weights needed to change the scale

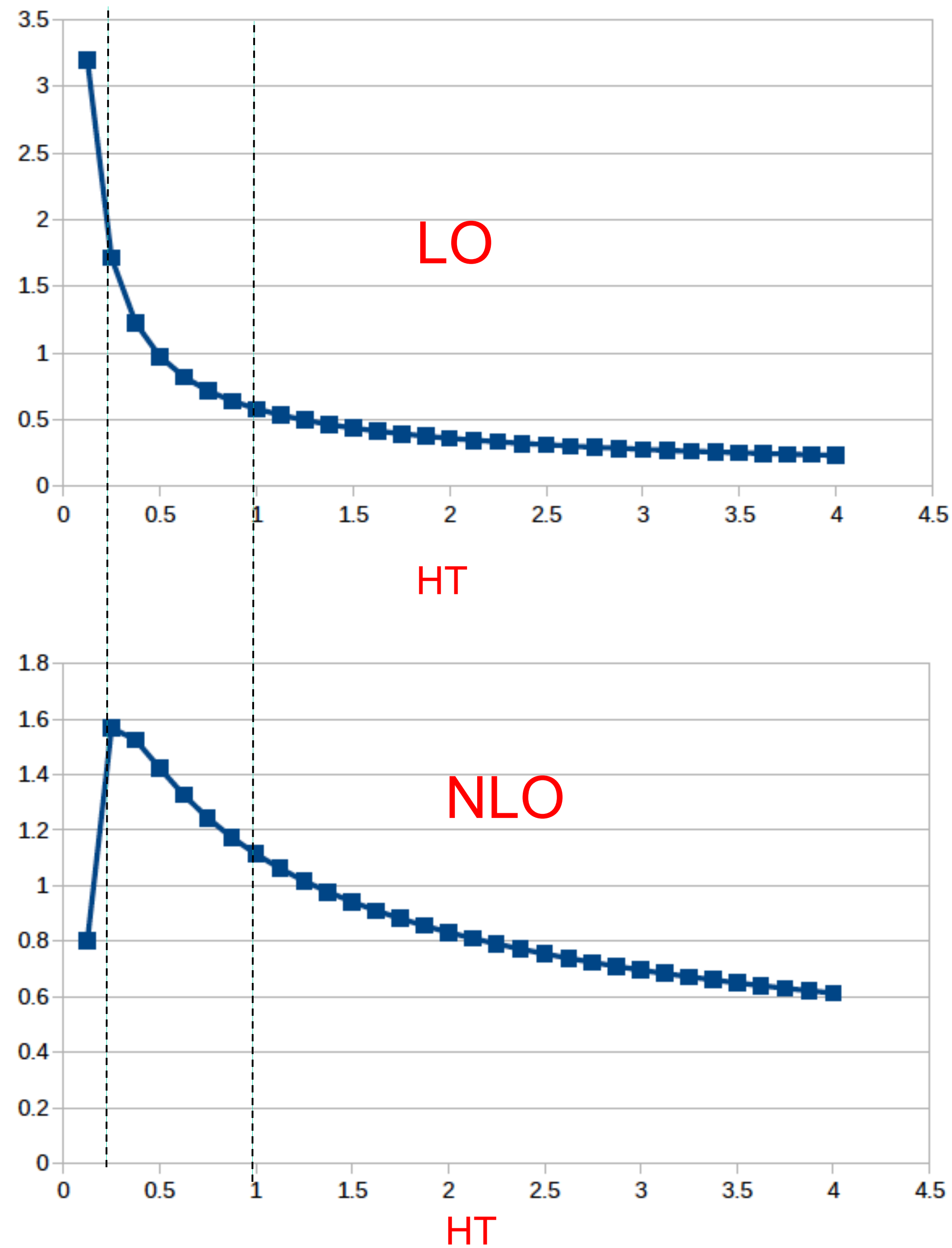
easy to calculate PDF, α_s, scale uncertainties

also results with different jet sizes/ Algorithms

ntuples ~14 TB for Higgs+>=3 jets

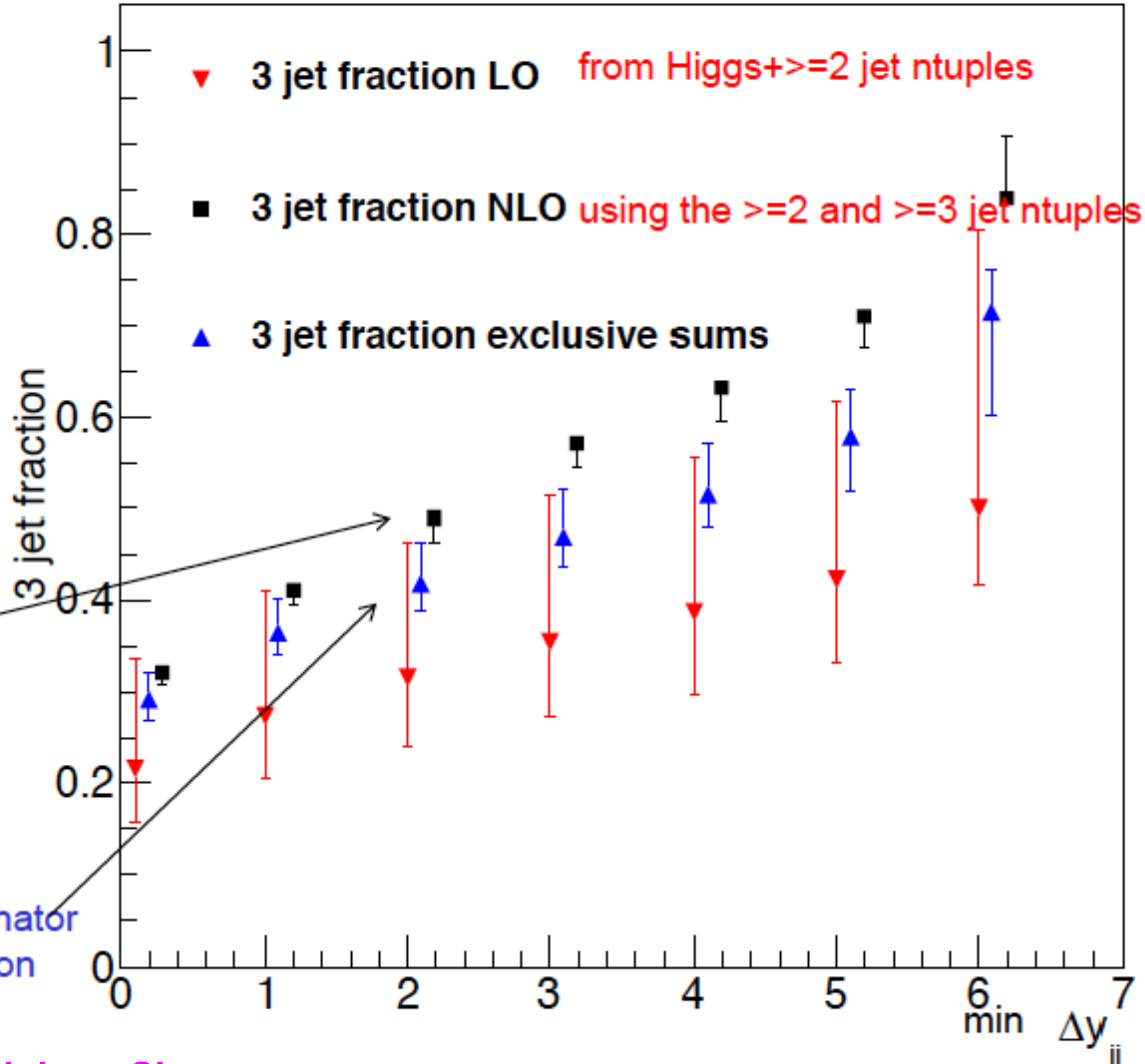

jet1_pT : H1j-ggf NLO 13TeV
Scale
PDF
σ = 13.2 pb
Ent: 1767701244
Jet alg: AntiKt4
PDF: CT10nlo
…from gosamHiggs+>=3 jet ntuples
dσ/dp_T, pb/GeV
p_T, GeV
jet2_pT : H2j-ggf NLO 13TeV
Scale
PDF
σ = 4.50 pb
Ent: 1390240701
Jet alg: AntiKt4
PDF: CT10nlo
dσ/dp_T, pb/GeV
p_T, GeV
jet3_pT : H3j-ggf NLO 13TeV
Scale
PDF
σ = 1.44 pb
Ent: 7234147048
Jet alg: AntiKt4
PDF: CT10nlo
dσ/dp_T, pb/GeV
p_T, GeV
jet4_pT : H3j-ggf NLO 13TeV
Scale
PDF
σ = 0.296 pb
Ent: 437815949
Jet alg: AntiKt4
PDF: CT10nlo
dσ/dp_T, pb/GeV
p_T, GeV

Scale dependence at LO and NLO for Higgs+>=3 jets from the gosam ntuples



An example

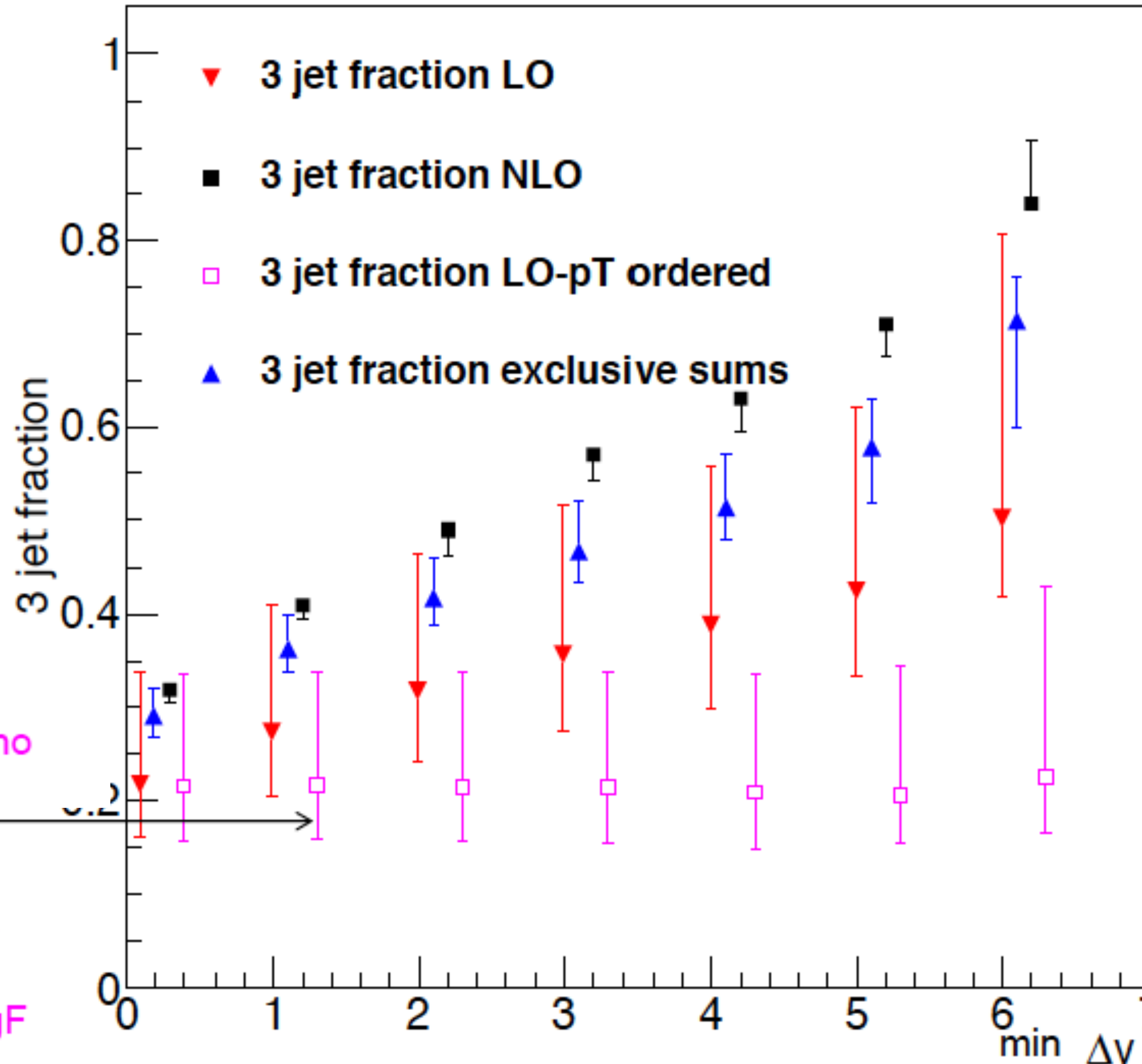
fraction of Higgs+>=2 jet events with a 3rd jet as a function of the minimum rapidity separation between the two most forward-backward jets.



note the small scale dependence for the 3 jet fraction NLO; fractions are larger since >=3 jet cross section is at NLO

exclusive sums fractions are somewhat smaller since >=2 jets in denominator gets increased contribution

Try this calculation with LoopSim.



if the p_T-ordered jets are used, then there's no logarithmic growth

This really doesn't take advantage of the QCD differences between ggF and VBF (if pileup jet suppression is sufficient).

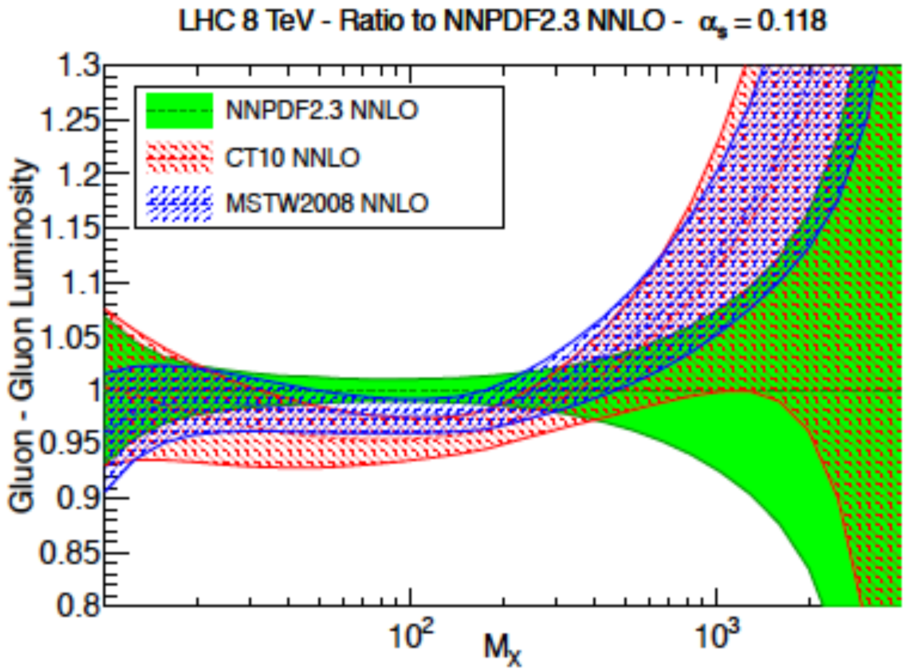
Is there any reason to have a dijet mass cut as well as a Δy_{jj} cut for VBF measurements?

…also with the ntuples

- We (almost universally) use a scale of $H_T/2$ for complex fixed order calculations, and the scale seems to work well, with variations a factor of 2 up and down to give uncertainties
- However, the optimal scale choice depends on kinematics and factors such as the jet size/algorithm
- **Can we understand this scale choice better for example through an implementation of the MINLO procedure in fixed order ntuples?**
- Can we adapt LoopSim to provide ~NNLO predictions for final states for which such calculations are not available?
  - **how well does it work for states for which NNLO is available?**

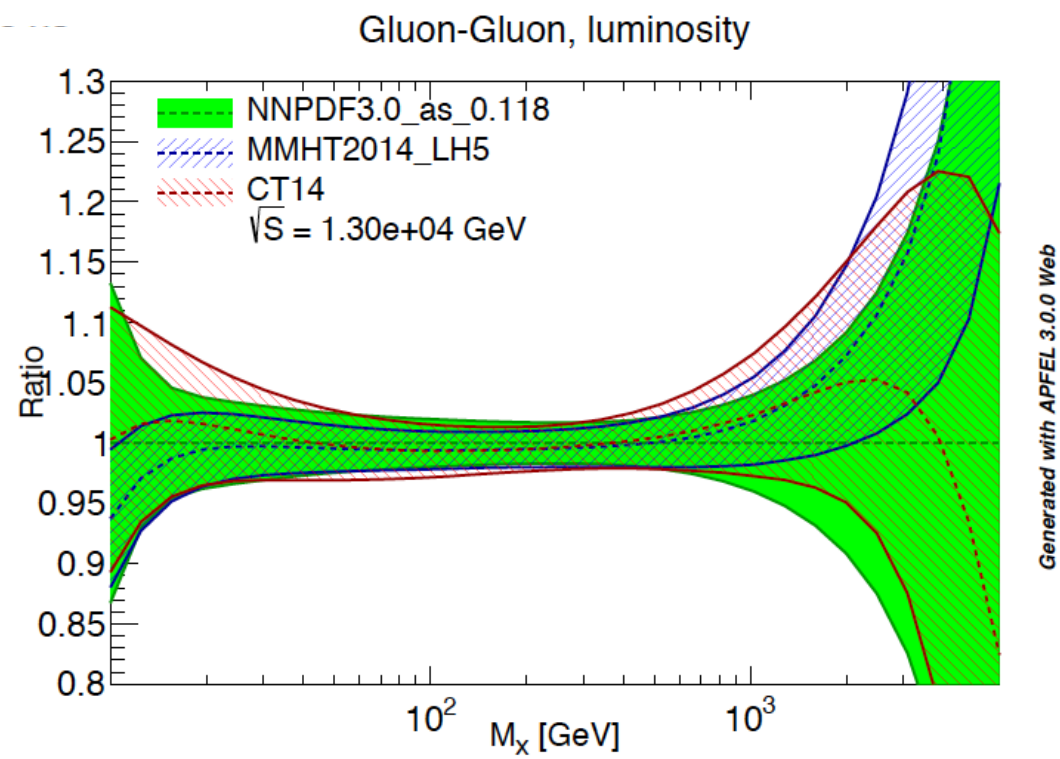
PDFs: the next generation

- NNPDF3.0 (arXiv:1410.8849)
- MMHT14 (arXiv:1412.3989)
- CT14
- HERAPDF2.0 (preliminary)
- Except for HERAPDF, all include data from the LHC, such as
  - inclusive jet->need full cross section at NNLO but corrections look to be small if scale of p_T^{jet} used
  - Drell-Yan
  - tT cross sections->need differential cross sections at NNLO (and EW corrections) to make full use of data
- HERAPDF2.0 includes the HERA2 combined data (not available for the other PDFs yet)
- Typically other improvements as well, such as in parametrizations



old story

new story



A comparison of ggF at NNLO

	CT14	MMHT2014	NNPDF3.0
8 TeV	18.66 pb -2.2% +2.0%	18.65 pb -1.9% +1.4%	18.77 pb -1.8% +1.8%
13 TeV	42.68 pb -2.4% +2.0%	42.70 pb -1.8% +1.3%	42.97 pb -1.9% +1.9%

The PDF uncertainty using this new generation of PDFs will be similar in size to the NNNLO scale uncertainty and to the $\alpha_s(m_Z)$ uncertainty.

Updating the PDF4LHC prescription

- We are working on an updated prescription, at NNLO and NLO, using information from CT14, MMHT14, NNPDF3.0, that have similar theoretical treatments/data sets
- This involves the use of a large number of error PDFs, but many programs are set up to do this in an automatic fashion
- There are some uses for which a smaller number of PDFs would be beneficial
  - for example, for programs where the automatic PDF re-weighting is not available
  - or where PDF uncertainties are treated as nuisance parameters, e.g. Higgs couplings
- We are currently examining two such techniques for reducing the number of error PDFs needed
  - META-PDFs
  - Compact Monte Carlo (CMC) PDFs
- See for example the presentation and discussion from PDF4LHC meeting
  - https://indico.cern.ch/event/355287/other-view?view=standard

Progress in developing the combination procedure

Two methods for combination of PDFs were extensively compared, with promising results:

1. **Meta-parametrizations + MC replicas + Hessian data set diagonalization** (J. Gao, J. Huston, P. Nadolsky, 1401.0013)
(META2.0 now implemented with very flexible parameterisation using Bernstein polynomials*)

2. **Compression of Monte-Carlo replicas** (Carazza, Latorre, Rojo, Watt, 1504:06469)

*scheduled for release during Les Houches

Both procedures start by creating a combined ensemble of MC replicas from all input ensembles (G. Watt, R. Thorne, 1205.4024; S. Forte, G. Watt, 1301.6754). They differ at the second step of reducing a large number of input MC replicas (~300) to a smaller number for practical applications (13-100 in the META approach; 40 in the CMC approach). The core question is how much input information to retain in the reduced replicas in each Bjorken-x region.

Pavel Nadolsky DIS2015

PDF4LHC meeting here Thursday afternoon

Benchmark comparisons, general observations II

PDF-PDF correlations:

Correlations of META300 and CMC300 ensembles differ by up to $\pm\, 0.2$ as a result of fluctuations in replica generation

META40 PDFs faithfully reproduce PDF-PDF correlations of the META600 PDFs in the regions with data; fail to reproduce correlations in extrapolation regions

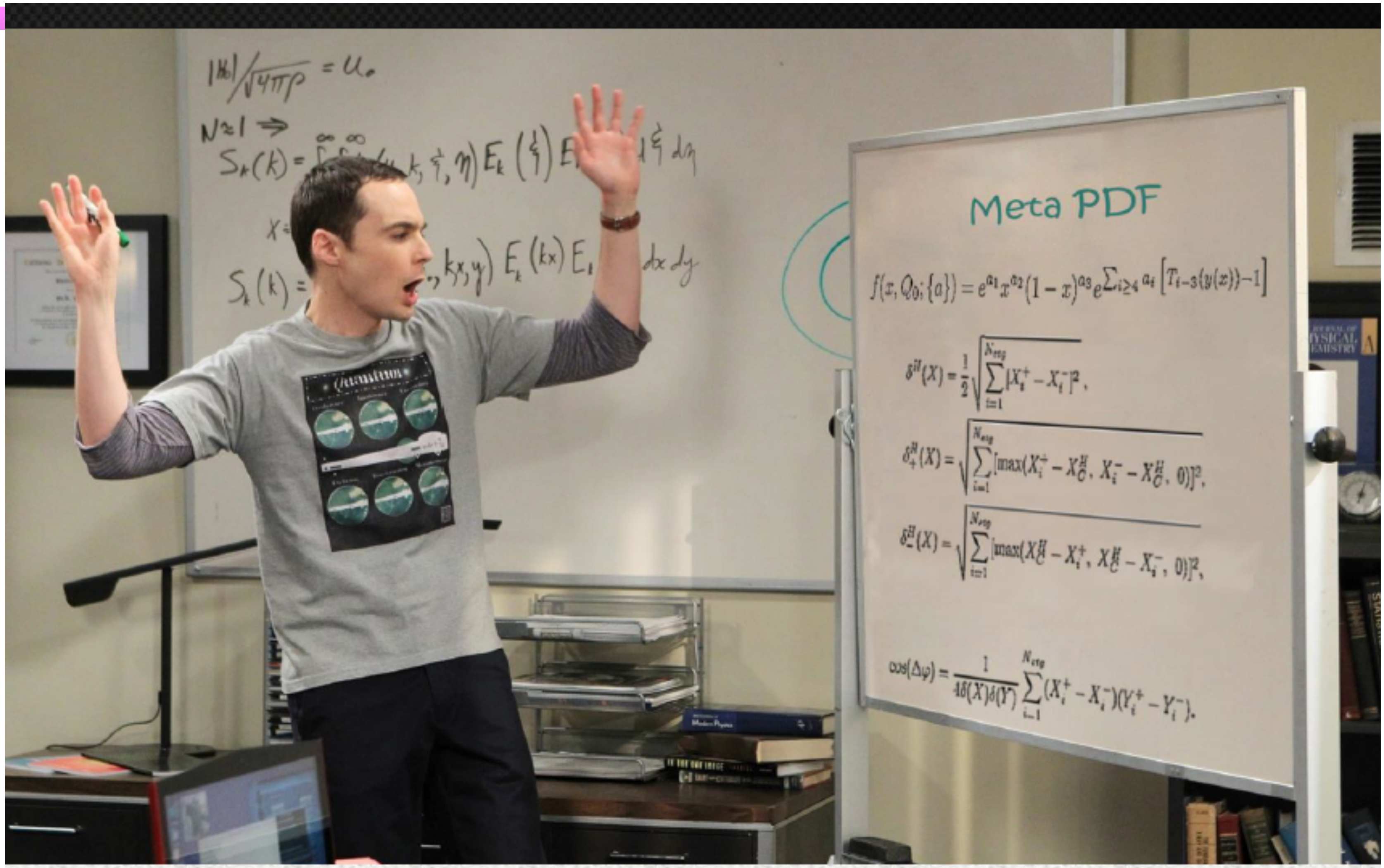
CMC40 PDFs better reproduce correlations of CMC300 in extrapolation regions; lose more accuracy in (x, Q) regions with data, but still within acceptable limits

These patterns of correlations persist at the initial scale $Q_0 = 8^*$ GeV as well as at EW scales

Pavel Nadolsky DIS2015

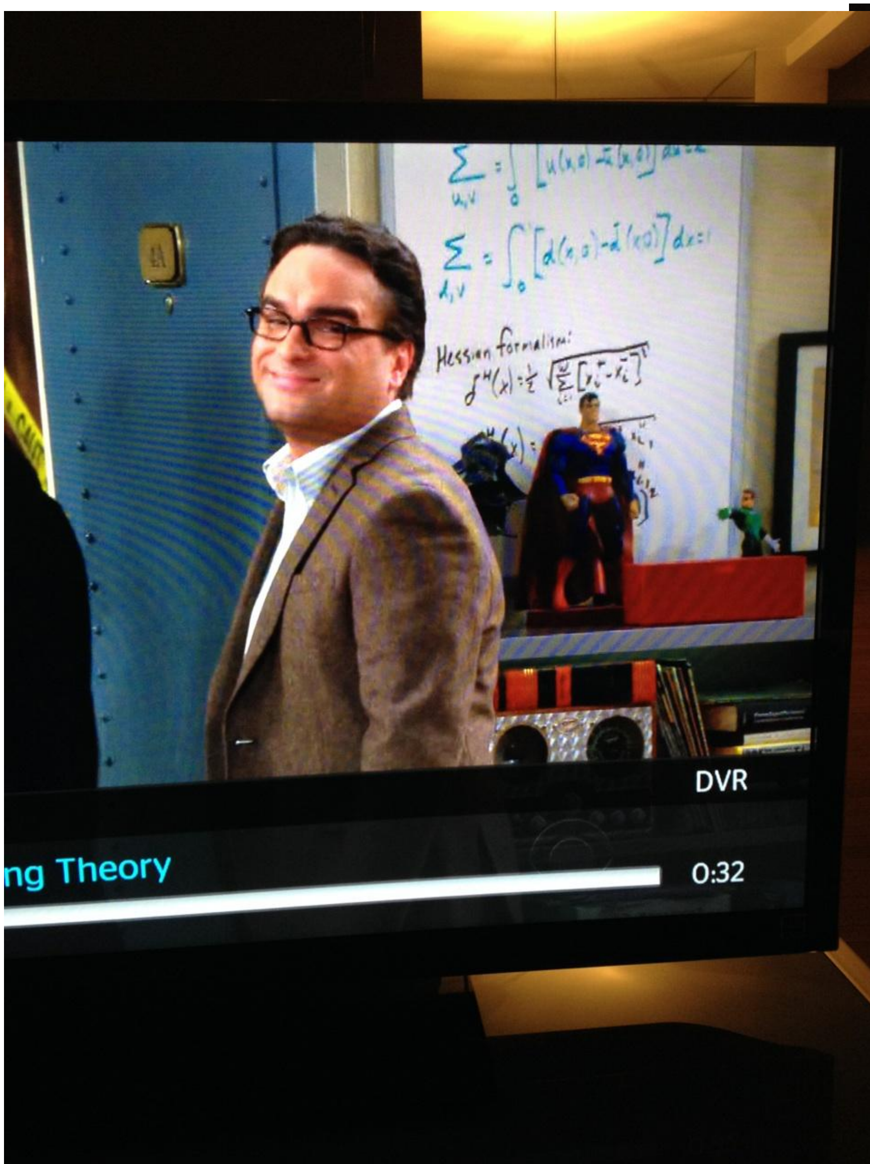
*note, below 8 GeV, details of individual heavy quark schemes become important

Of course, only one of these appeared on BBT



Jun, Pavel,

Sheldon approves! META PDFs will be on the Big Bang Theory episode on Jan. 29, 2015. Regards, Joey


DVR
ng Theory
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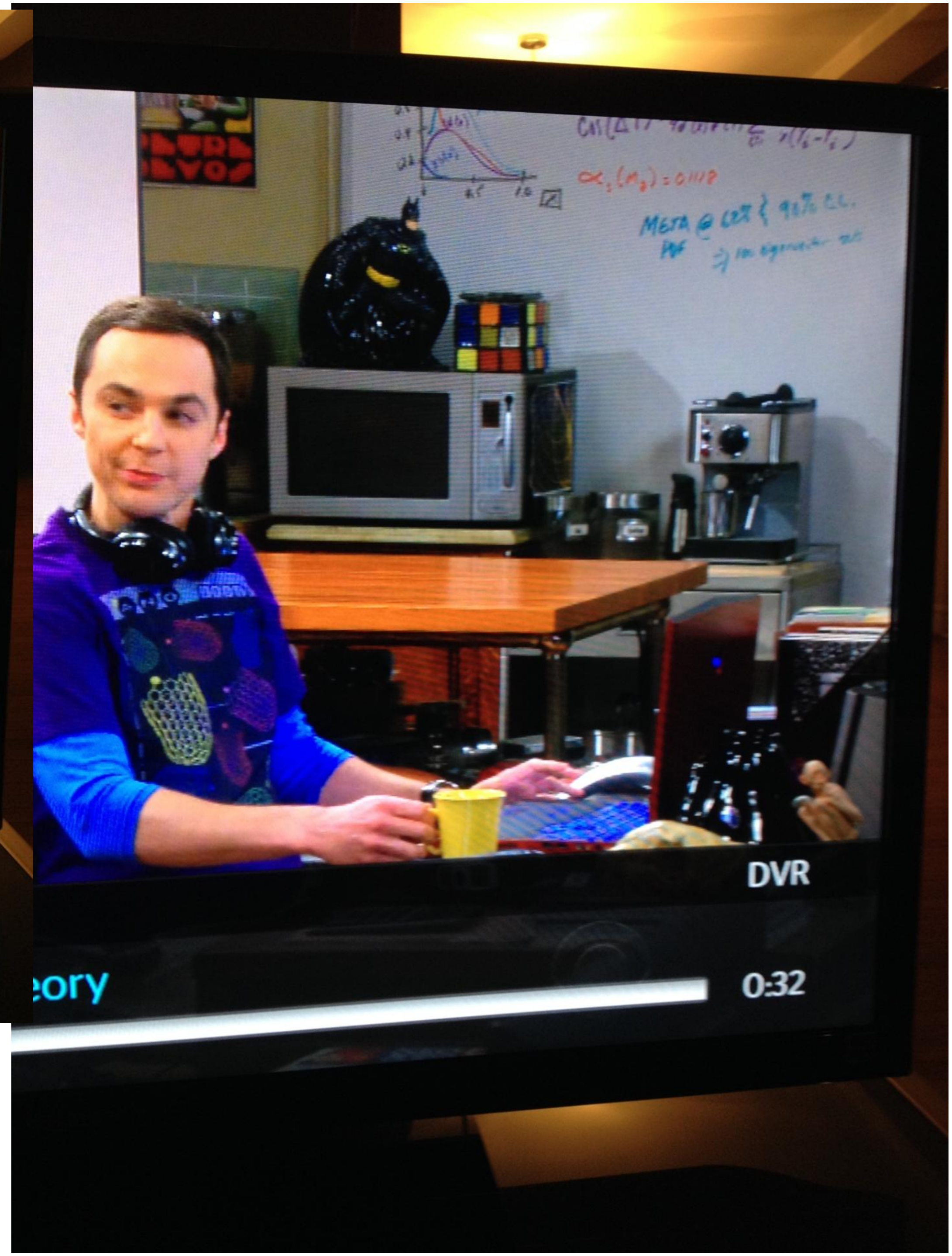
DVR
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NNLO QCD + NLO EWK wishlist

heavy quarks, photons, jets

Process	known	desired	details
$t\bar{t}$	$\sigma_{\rm tot}$ @ NNLO QCD $d\sigma$(top decays) @ NLO QCD $d\sigma$(stable tops) @ NLO EW	$d\sigma$(top decays) @ NNLO QCD + NLO EW	precision top/QCD, gluon PDF, effect of extra radiation at high rapidity, top asymmetries
$t\bar{t} + j$	$d\sigma$(NWA top decays) @ NLO QCD	$d\sigma$(NWA top decays) @ NNLO QCD + NLO EW	precision top/QCD top asymmetries
single-top	$d\sigma$(NWA top decays) @ NLO QCD	$d\sigma$(NWA top decays) @ NNLO QCD (t channel)	precision top/QCD, V_{tb}
dijet	$d\sigma$ @ NNLO QCD (g only) $d\sigma$ @ NLO weak	$d\sigma$ @ NNLO QCD + NLO EW	Obs.: incl. jets, dijet mass $\rightarrow$ PDF fits (gluon at high x) $\rightarrow \alpha_s$ CMS http://arxiv.org/abs/1212.6660
3j	$d\sigma$ @ NLO QCD	$d\sigma$ @ NNLO QCD + NLO EW	Obs.: $R3/2$ or similar $\rightarrow \alpha_s$ at high scales dom. uncertainty: scales CMS http://arxiv.org/abs/1304.7498
$\gamma + j$	$d\sigma$ @ NLO QCD $d\sigma$ @ NLO EW	$d\sigma$ @ NNLO QCD +NLO EW	gluon PDF $\gamma + b$ for bottom PDF

Table 2: Wishlist part 2 – jets and heay quarks

NNLO QCD + NLO EWK wishlist

- One of key processes for perturbative QCD
  - covers largest kinematic range with jets produced in the multi-TeV range
  - EW effects very important in this range
- Only process currently included in global fits not known at NNLO
  - gg channel has been calculated
- Current experimental precision on the order of 5-10% for jets from 200 GeV/c to 1 TeV/c
- Would like better precision for theory
  - so need NNLO QCD and NLO EW
- **We also need a better understanding of the impact of parton showers on the fixed order cross section**

Process	State of the Art	Desired
$t\bar{t}$	σ_{tot}(stable tops) @ NNLO QCD $d\sigma$(top decays) @ NLO QCD $d\sigma$(stable tops) @ NLO EW	$d\sigma$(top decays) @ NNLO QCD + NLO EW
$t\bar{t}+j(j)$	$d\sigma$(NWA top decays) @ NLO QCD	$d\sigma$(NWA top decays) @ NNLO QCD + NLO EW
$t\bar{t}+Z$	$d\sigma$(stable tops) @ NLO QCD	$d\sigma$(top decays) @ NLO QCD + NLO EW
single-top	$d\sigma$(NWA top decays) @ NLO QCD	$d\sigma$(NWA top decays) @ NNLO QCD + NLO EW
dijet	$d\sigma$ @ NNLO QCD (g only) $d\sigma$ @ NLO EW (weak)	$d\sigma$ @ NNLO QCD + NLO EW
3j	$d\sigma$ @ NLO QCD	$d\sigma$ @ NNLO QCD + NLO EW
$\gamma+j$	$d\sigma$ @ NLO QCD $d\sigma$ @ NLO EW	$d\sigma$ @ NNLO QCD + NLO EW

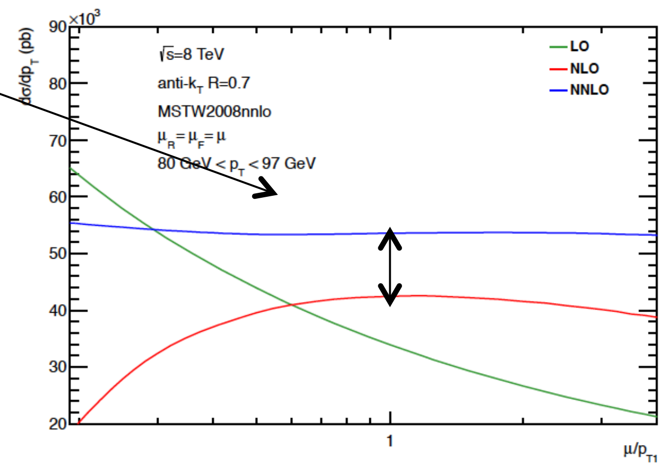


FIG. 2: Scale dependence of the inclusive jet cross section for pp collisions at $\sqrt{s}=8$ TeV for the anti-k_T algorithm with $R=0.7$ and with $|y|<4.4$ and $80\text{ GeV} < p_T < 97$ GeV at NNLO (blue), NLO (red) and LO (green).

NB: relatively large corrections

…but, arXiv:1407.7031

- NNLO/NLO corrections smaller (on the order of 5%) and flat as a function of jet p_T if scale of inclusive jet p_T is used rather than p_T of the lead jet
- …which is what should be used in any case
- expect corrections for other subprocesses to be of similar order

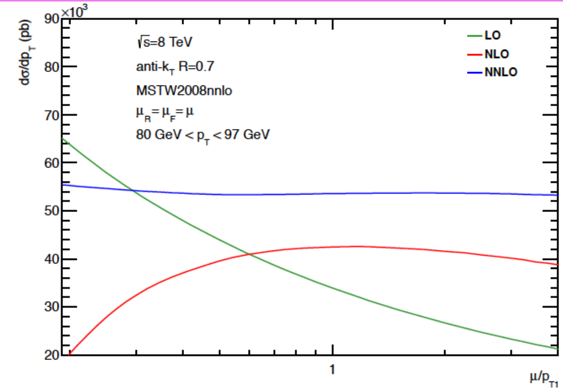


FIG. 2: Scale dependence of the inclusive jet cross section for pp collisions at $\sqrt{s} = 8$ TeV for the anti-k_T algorithm with $R = 0.7$ and with $|y| < 4.4$ and 80 GeV $< p_T <$ 97 GeV at NNLO (blue), NLO (red) and LO (green).

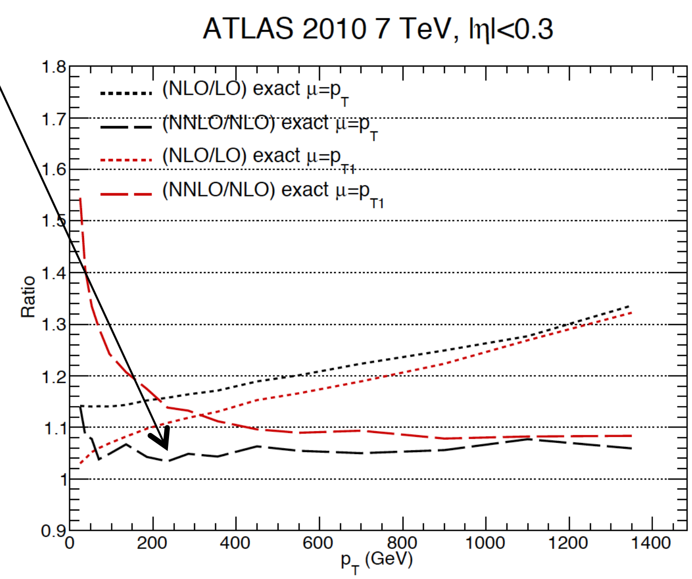
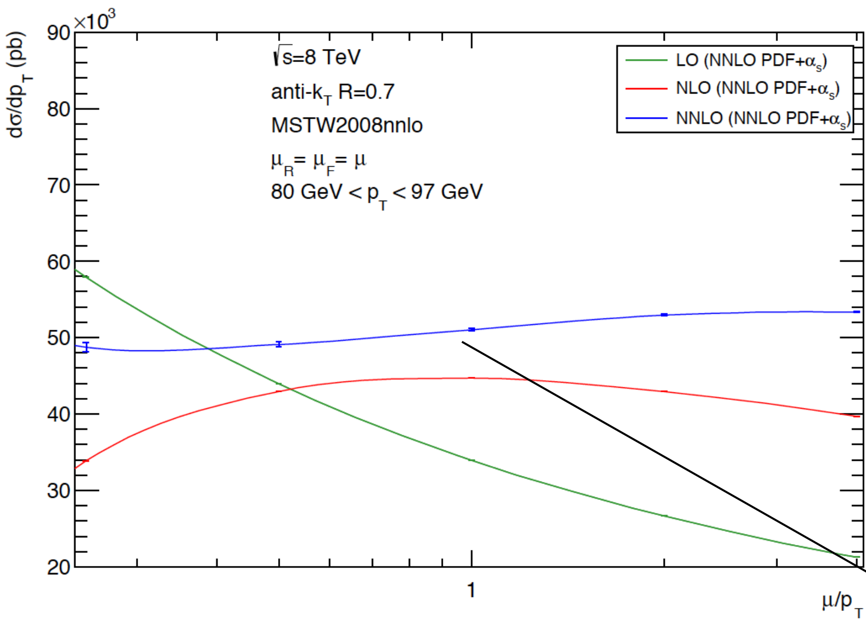


Figure 8: NLO/LO and NNLO/NLO exact k-factors for the gg-channel evaluated with the renormalisation and factorisation scales $\mu_R = \mu_F = p_T$ and $\mu_R = \mu_F = p_{T1}$.

…but, revision of the paper

- The referee made the same request I did, to show the plot to the right using a scale of p_T, rather than p_{T1}



- Note that NLO goes up (as expected) but NNLO also comes down…and a bit more scale dependence

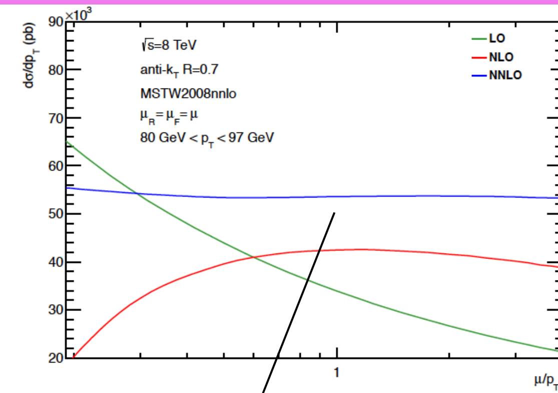


FIG. 2: Scale dependence of the inclusive jet cross section for pp collisions at $\sqrt{s} = 8$ TeV for the anti-k_T algorithm with $R = 0.7$ and with $|y| < 4.4$ and 80 GeV $< p_T <$ 97 GeV at NNLO (blue), NLO (red) and LO (green).

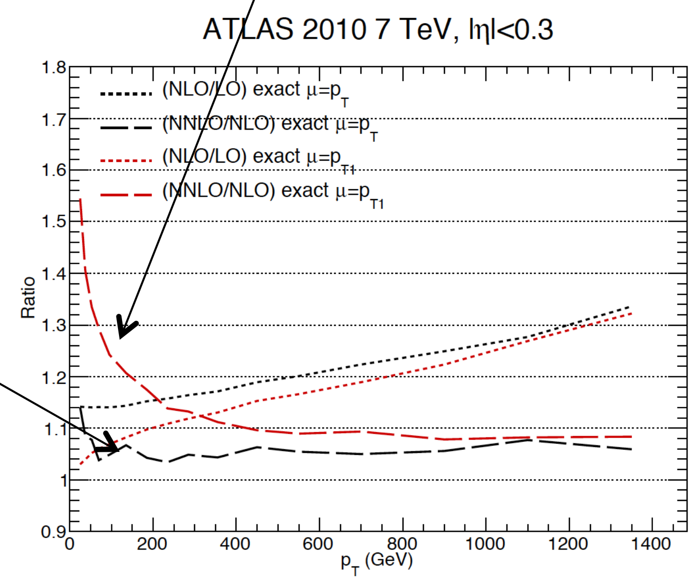
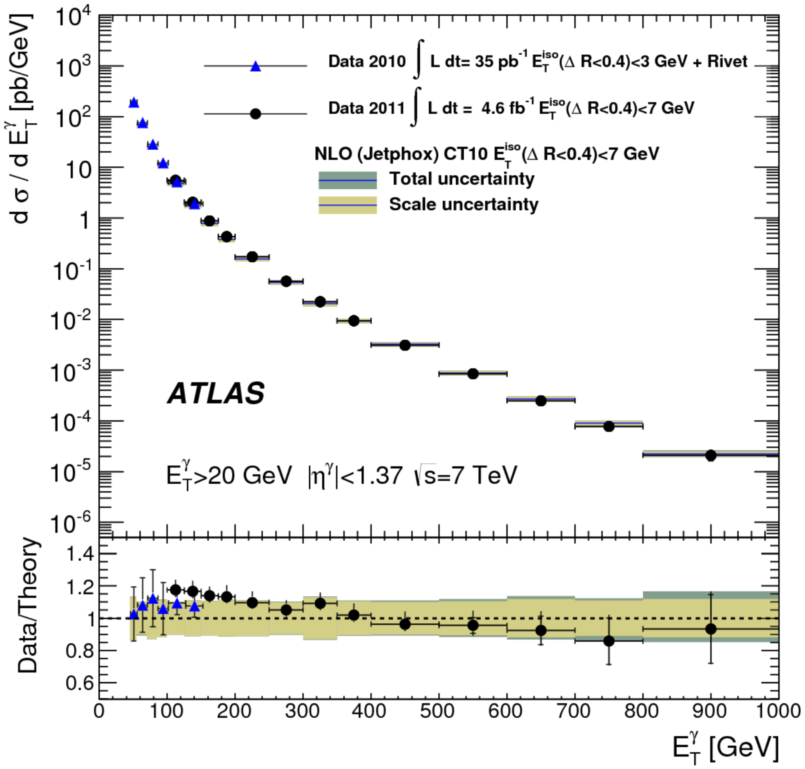


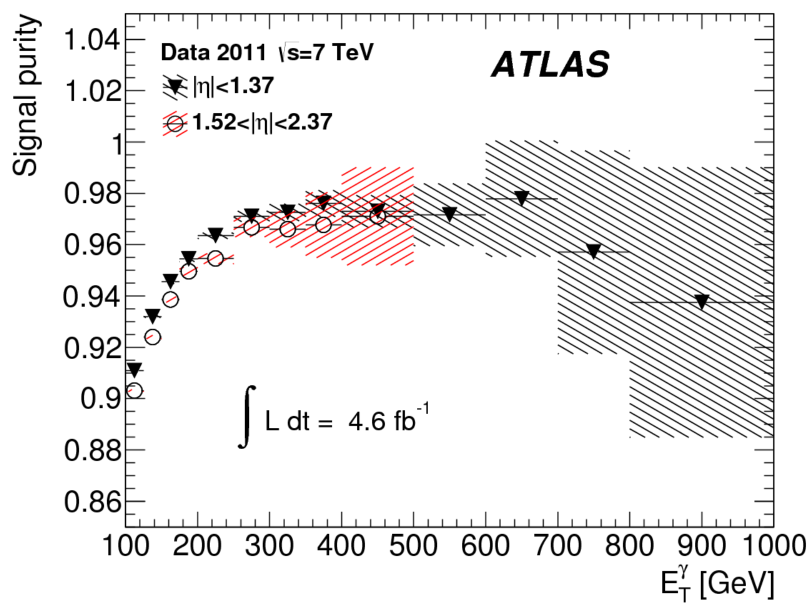
Figure 8: NLO/LO and NNLO/NLO exact k-factors for the gg-channel evaluated with the renormalisation and factorisation scales $\mu_R = \mu_F = p_T$ and $\mu_R = \mu_F = p_{T1}$.

NNLO QCD + NLO EWK wishlist

- Useful for determination of the gluon distribution, especially at high x
- Final state cleaner than dijet production (at high p_T)
- So like the dijet case, would like to know γ+j production at NNLO QCD +NLO EW

Process	State of the Art	Desired
$t\bar{t}$	σ_{tot}(stable tops) @ NNLO QCD $d\sigma$(top decays) @ NLO QCD $d\sigma$(stable tops) @ NLO EW	$d\sigma$(top decays) @ NNLO QCD + NLO EW
$t\bar{t}+j(j)$	$d\sigma$(NWA top decays) @ NLO QCD	$d\sigma$(NWA top decays) @ NNLO QCD + NLO EW
$t\bar{t}+Z$	$d\sigma$(stable tops) @ NLO QCD	$d\sigma$(top decays) @ NLO QCD + NLO EW
single-top	$d\sigma$(NWA top decays) @ NLO QCD	$d\sigma$(NWA top decays) @ NNLO QCD + NLO EW
dijet	$d\sigma$ @ NNLO QCD (g only) $d\sigma$ @ NLO EW (weak)	$d\sigma$ @ NNLO QCD + NLO EW
3j	$d\sigma$ @ NLO QCD	$d\sigma$ @ NNLO QCD + NLO EW
$\gamma+j$	$d\sigma$ @ NLO QCD $d\sigma$ @ NLO EW	$d\sigma$ @ NNLO QCD + NLO EW





Note any isolated high p_T EM object is a photon …if not in your analysis, then why not

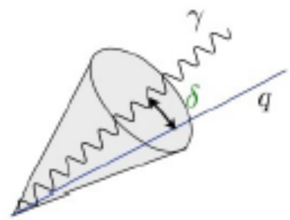
Photon production

- Experimentally photons must be isolated
- Isolation reduces fragmentation component → Large Corrections

Isolation criteria

- **Standard (cone)** Baer, Ohnemus, Owens (1990). Aurenche, Baier, Fontannaz (1990)

$$\sum_{\delta<R_0} E_T^{had} \leq \varepsilon_\gamma p_T^\gamma$$



$$\sum_{\delta<R_0} E_T^{had} \leq E_T^{max}$$

- **Smooth (Frixione)** S. Frixione (1998)

$$\chi(\delta) = \left(\frac{1-\cos(\delta)}{1-\cos(R_0)} \right)^n \leq 1$$

$$\sum_{\delta<R_0} E_T^{had} \leq E_T^{max} \chi(\delta)$$

- **Democratic** Glover, Morgan(1994). Gehrmann-De Ridder, Gehrmann, Glover (1997)

final state particles are clustered into jets, **<u>treating photons and hadrons equally.</u>** The obtained object is called a photon or a photon jet, if the energy fraction **Z = Eγ/(Eγ + Ehad)** of an observed photon inside the jet is larger than an experimentally defined value **Zcut**.

Les Houches accord 2013

[Les Houches 2013: Physics at TeV Colliders: Standard Model Working Group Report]

"LH tight photon isolation accord"

- EXP: use (tight) Cone isolation — solid and well understood
- TH: use smooth cone with same R and E_{Tmax} — accurate, better than using cone with LO fragmentation

Estimate TH isolation uncertainties using different profiles in smooth cone

Considering that NNLO corrections are of the order of 50% for diphoton cross sections and a few 100% for some distributions in extreme kinematical configurations, it is far better accepting a few % error arising from the isolation (less than the size of the expected NNNLO corrections and within any estimate of TH uncertainties!) than neglecting those huge QCD effects towards some "more pure implementation" of the isolation prescription.

Recently, some calculations use the smooth cone isolation criteria to arrive at the highest level of accuracy:

Vγ production [NNLO] M. Grazzini, S. Kallweit, D. Rathlev, A. Torre (2013), (2015)

γγ + 2Jets [NLO] T. Gehrmann , N. Greiner , G. Heinrich (2013) ;Z. Bern, L.J. Dixon, F. Febres Cordero, S. Hoeche, H. Ita, D.A. Kosower, N. A. Lo Presti, D. Maitre (2013)

γγ + (up to) 3Jets [NLO] S. Badger, A. Guffanti, V. Yundin (2013)

Les Houches accord 2013

[Les Houches 2013: Physics at TeV Colliders: Standard Model Working Group Report]

"LH tight photon isolation accord"

Can we quantify for more processes?

- EXP: use (tight) Cone isolation — solid and well understood
- TH: use smooth cone with same R and E_{Tmax} — accurate, better than using cone with LO fragmentation

Estimate TH isolation uncertainties using different profiles in smooth cone

While the definition of "tight enough" might slightly depend on the particular observable (that can always be checked by a lowest order calculation), our analysis shows that at the LHC isolation parameters as $E_T^{max} \leq 5$ GeV (or $\epsilon < 0.1$), $R \sim 0.4$ and $R_{\gamma\gamma} \sim 0.4$ are safe enough to proceeed.

This procedure would allow to extend available NLO calculations to one order higher (NNLO) for a number of observables, since the direct component is always much simpler to evaluate than the fragmentation part, which identically vanishes under the smooth cone isolation.

NNLO QCD + NLO EWK wishlist

Vector bosons

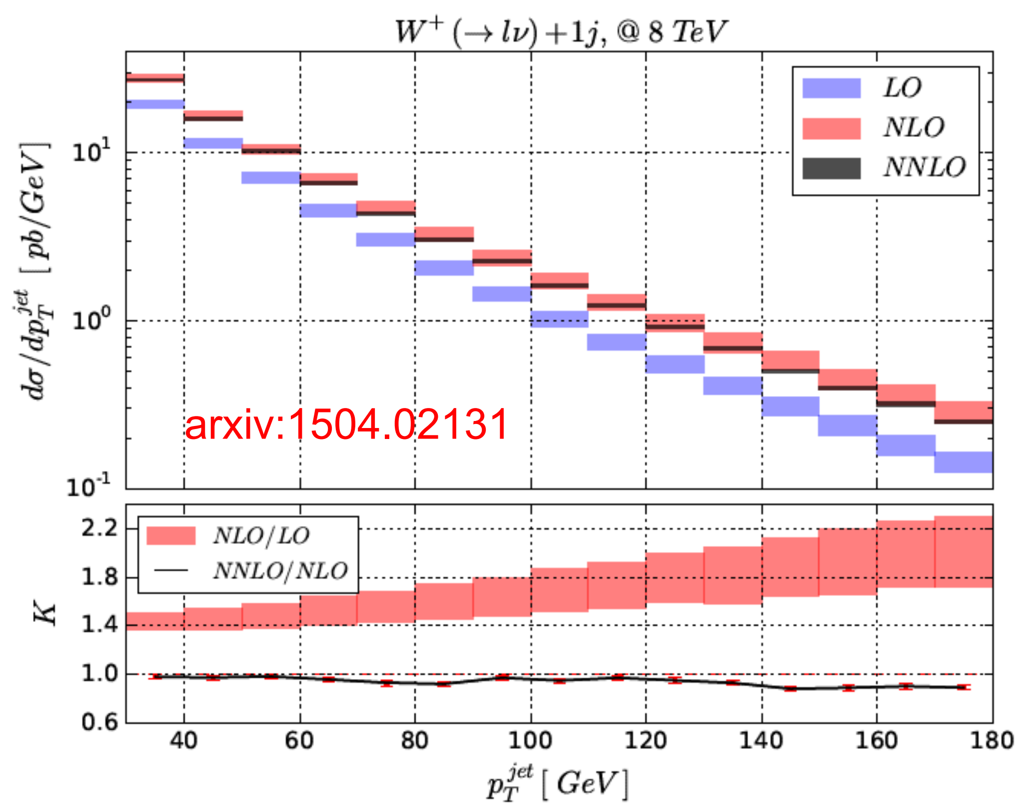
Process	known	desired	details
V	$d\sigma$(lept. V decay) @ NNLO QCD $d\sigma$(lept. V decay) @ NLO EW	$d\sigma$(lept. V decay) @ NNNLO QCD + NLO EW MC@NNLO	precision EW, PDFs
$\mathrm{V+j}$	$d\sigma$(lept. V decay) @ NLO QCD $d\sigma$(lept. V decay) @ NLO EW	$d\sigma$(lept. V decay) @ NNLO QCD + NLO EW	$\mathrm{Z+j}$ for gluon PDF $\mathrm{W+c}$ for strange PDF
$\mathrm{V+jj}$	$d\sigma$(lept. V decay) @ NLO QCD	$d\sigma$(lept. V decay) @ NNLO QCD + NLO EW	study of systematics of $\mathrm{H+jj}$ final state
$\mathrm{VV'}$	$d\sigma$(V decays) @ NLO QCD $d\sigma$(stable V) @ NLO EW	$d\sigma$(V decays) @ NNLO QCD + NLO EW	off-shell leptonic decays TGCs
$\mathrm{gg} \to \mathrm{VV}$	$d\sigma$(V decays) @ LO QCD	$d\sigma$(V decays) @ NLO QCD	bkg. to $H \to VV$ TGCs
$\mathrm{V}\gamma$	$d\sigma$(V decay) @ NLO QCD $d\sigma$(PA, V decay) @ NLO EW	$d\sigma$(V decay) @ NNLO QCD + NLO EW	TGCs
$\mathrm{Vb\bar{b}}$	$d\sigma$(lept. V decay) @ NLO QCD massive b	$d\sigma$(lept. V decay) @ NNLO QCD massless b	bkg. for $\mathrm{VH} \to \mathrm{b\bar{b}}$
$\mathrm{VV'}\gamma$	$d\sigma$(V decays) @ NLO QCD	$d\sigma$(V decays) @ NLO QCD + NLO EW	QGCs
$\mathrm{VV'V''}$	$d\sigma$(V decays) @ NLO QCD	$d\sigma$(V decays) @ NLO QCD + NLO EW	QGCs, EWSB
$\mathrm{VV'+j}$	$d\sigma$(V decays) @ NLO QCD	$d\sigma$(V decays) @ NLO QCD + NLO EW	bkg. to H, BSM searches
$\mathrm{VV'+jj}$	$d\sigma$(V decays) @ NLO QCD	$d\sigma$(V decays) @ NLO QCD + NLO EW	QGCs, EWSB
$\gamma\gamma$	$d\sigma$ @ NNLO QCD		bkg to $H \to \gamma\gamma$

Table 3: Wishlist part 3 – EW gauge bosons ($\mathrm{V = W, Z}$)

NNLO QCD + NLO EWK wishlist

- Useful for PDF determination
  - Z+jet for gluon determination
  - W+c for strange quark determination
- Useful to study systematics of multiple jet production in a system with a large mass (->Higgs), with a wide accessible kinematic range
- Currently know W+>=1 jet to NNLO QCD
  - cross section seems very stable
- V+1-5 jets to NLO QCD; NLO EW corrections known for V+1 jet, including V decays and off-shell effects
- For Z+2 jets, NLO EW corrections known for on-shell, and are in progress for off-shell
- Differential theoretical uncertainties can reach 10-20% for high jet momenta, exceeding experimental uncertainties

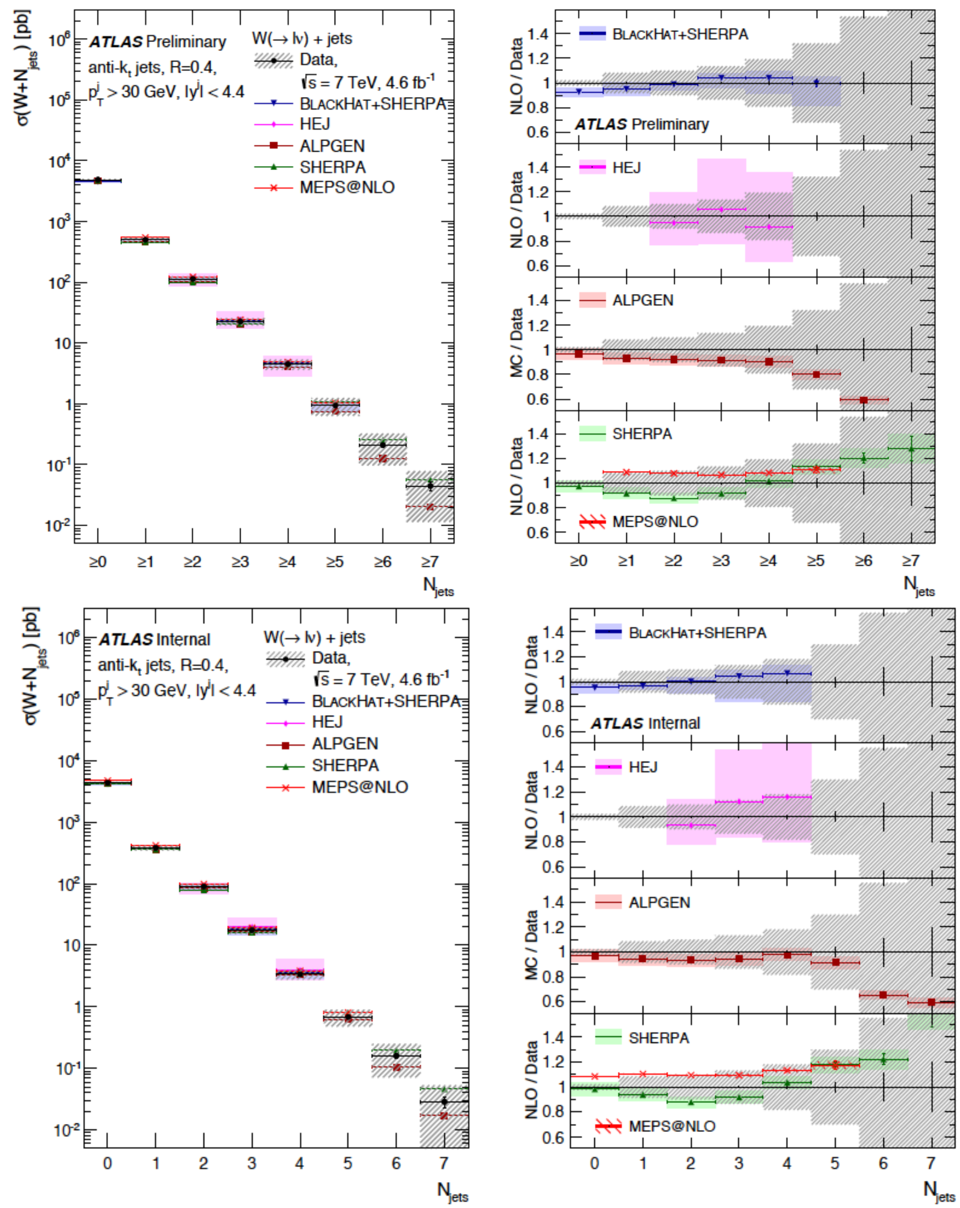
Process	known	desired	details
V	$d\sigma$(lept. V decay) @ NNLO QCD $d\sigma$(lept. V decay) @ NLO EW	$d\sigma$(lept. V decay) @ NNNLO QCD + NLO EW MC@NNLO	precision EW, PDFs
V + j	$d\sigma$(lept. V decay) @ NLO QCD $d\sigma$(lept. V decay) @ NLO EW	$d\sigma$(lept. V decay) @ NNLO QCD + NLO EW	Z + j for gluon PDF W + c for strange PDF
V + jj	$d\sigma$(lept. V decay) @ NLO QCD	$d\sigma$(lept. V decay) @ NNLO QCD + NLO EW	study of systematics of H + jj final state
VV′	$d\sigma$(V decays) @ NLO QCD	$d\sigma$(V decays)	off shell leptonic decays



Would like to know both cross sections at NNLO QCD+NLO EW

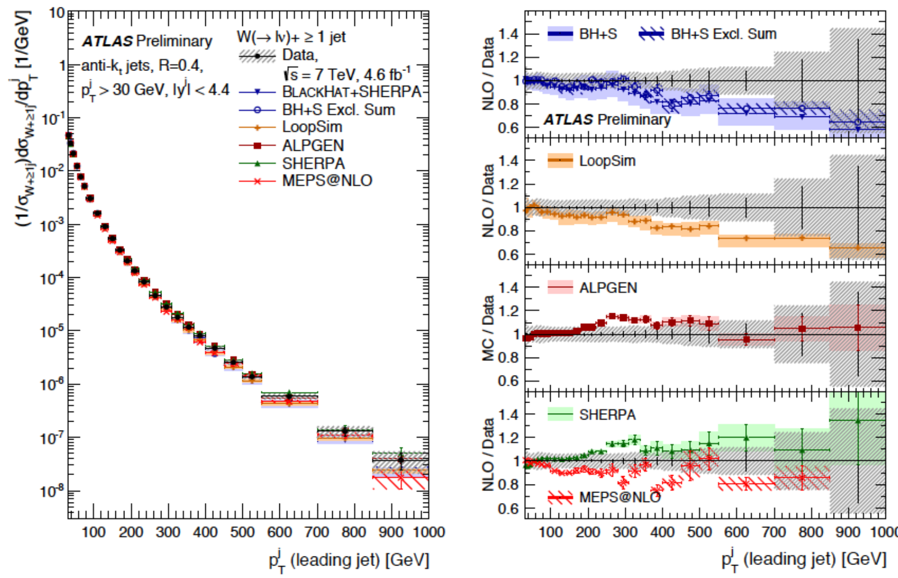
W+jets

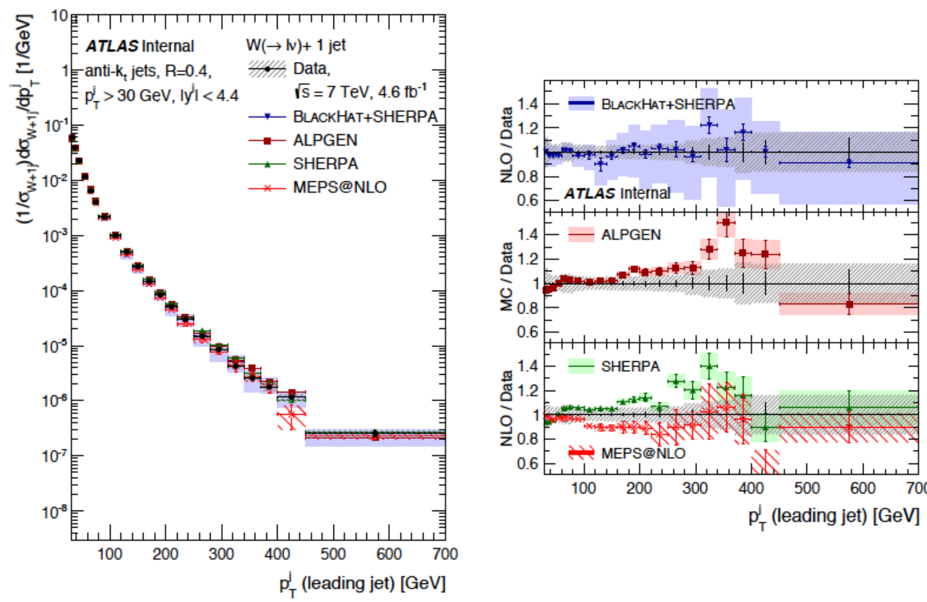
- ATLAS has measured up to 7 jets in the final state
  - both inclusive and exclusive final states
  - good agreement with Blackhat+Sherpa in general



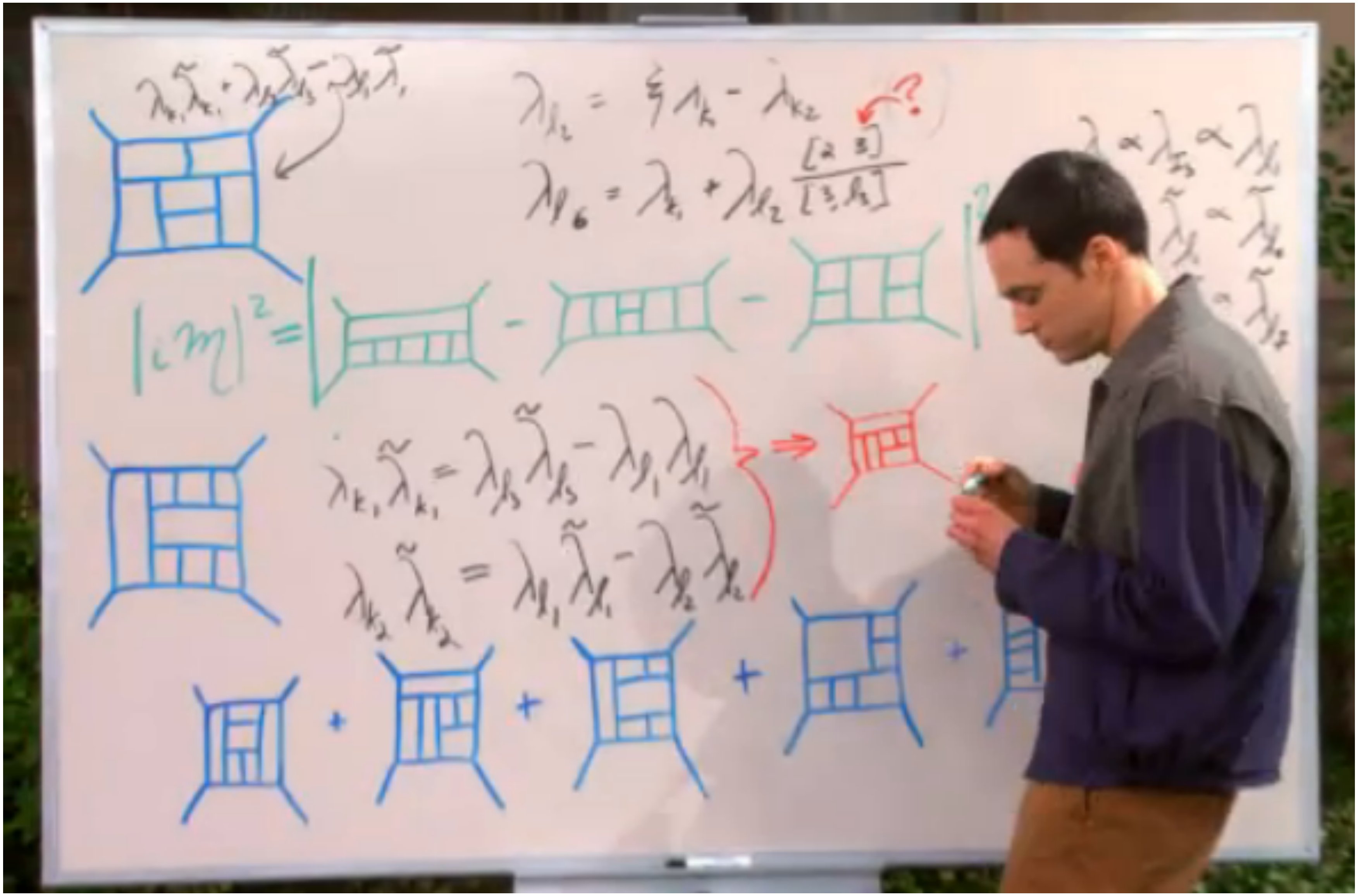
Leading jet p_T

- Inclusive leading jet p_T distribution higher than NLO prediction at high transverse momentum
  - 1 TeV/c!
- Exclusive lead jet p_T agrees very well with NLO prediction up to 700 GeV/c
  - why should fixed order work so well when such an exclusive final state is probed?->jet veto logs
- arXiv:1501.01059
  - R. Boughezal et al
  - due to ATLAS analysis, additional jet allowed if it is collinear to a lepton
- **Better understanding? ATLAS/CMS differences?**





The frontier



Summary

- The new high precision Les Houches wishlist presents some real (and important) challenges for QCD and EW calculators
- There is a lot of related phenomenology that needs to be done to make best use of this theoretical progress
- The data to be taken in Run 2 requires the effort
- Data from Run 2 is in progress.
- **Don't wait.**

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