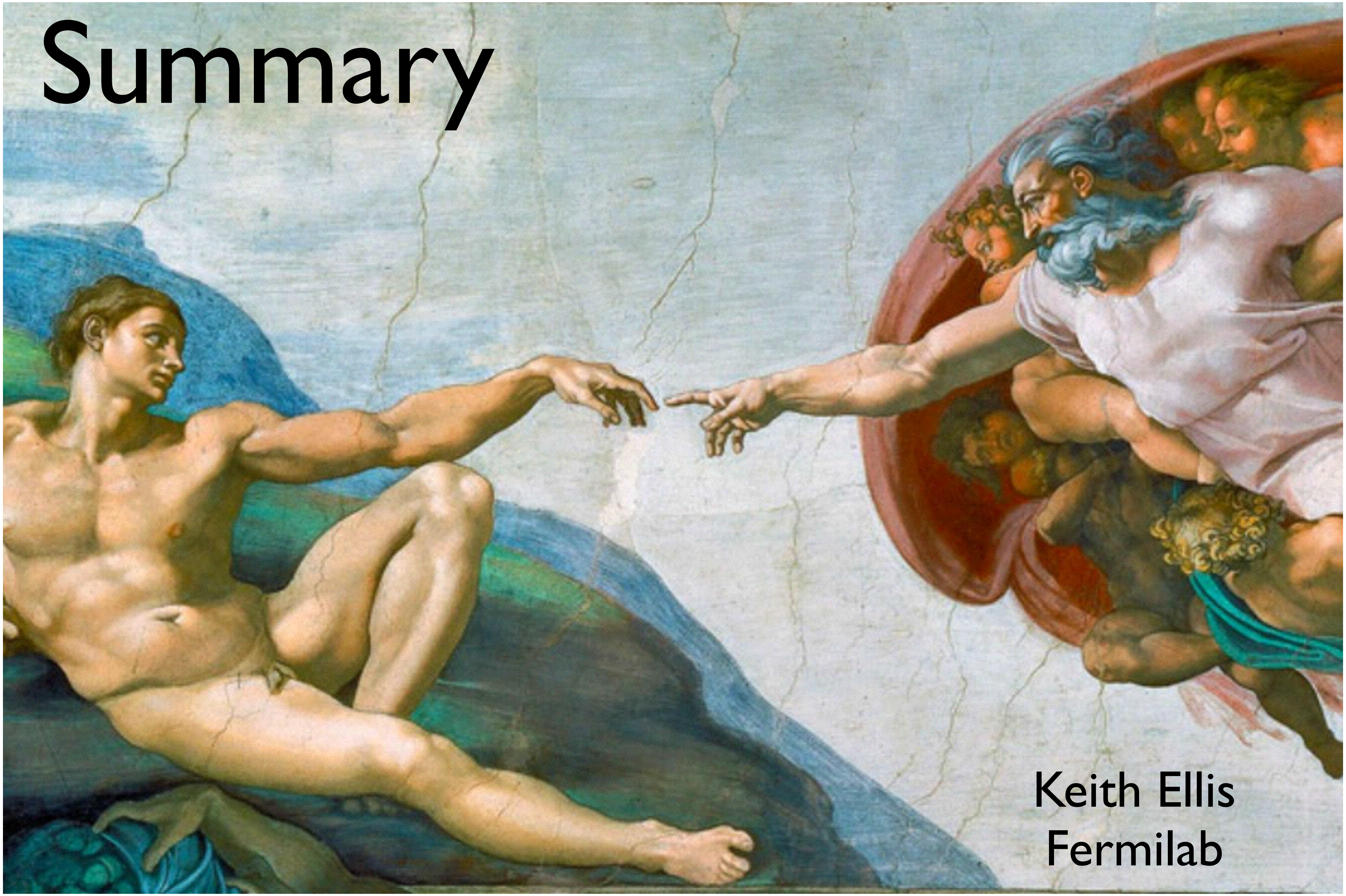
Summary

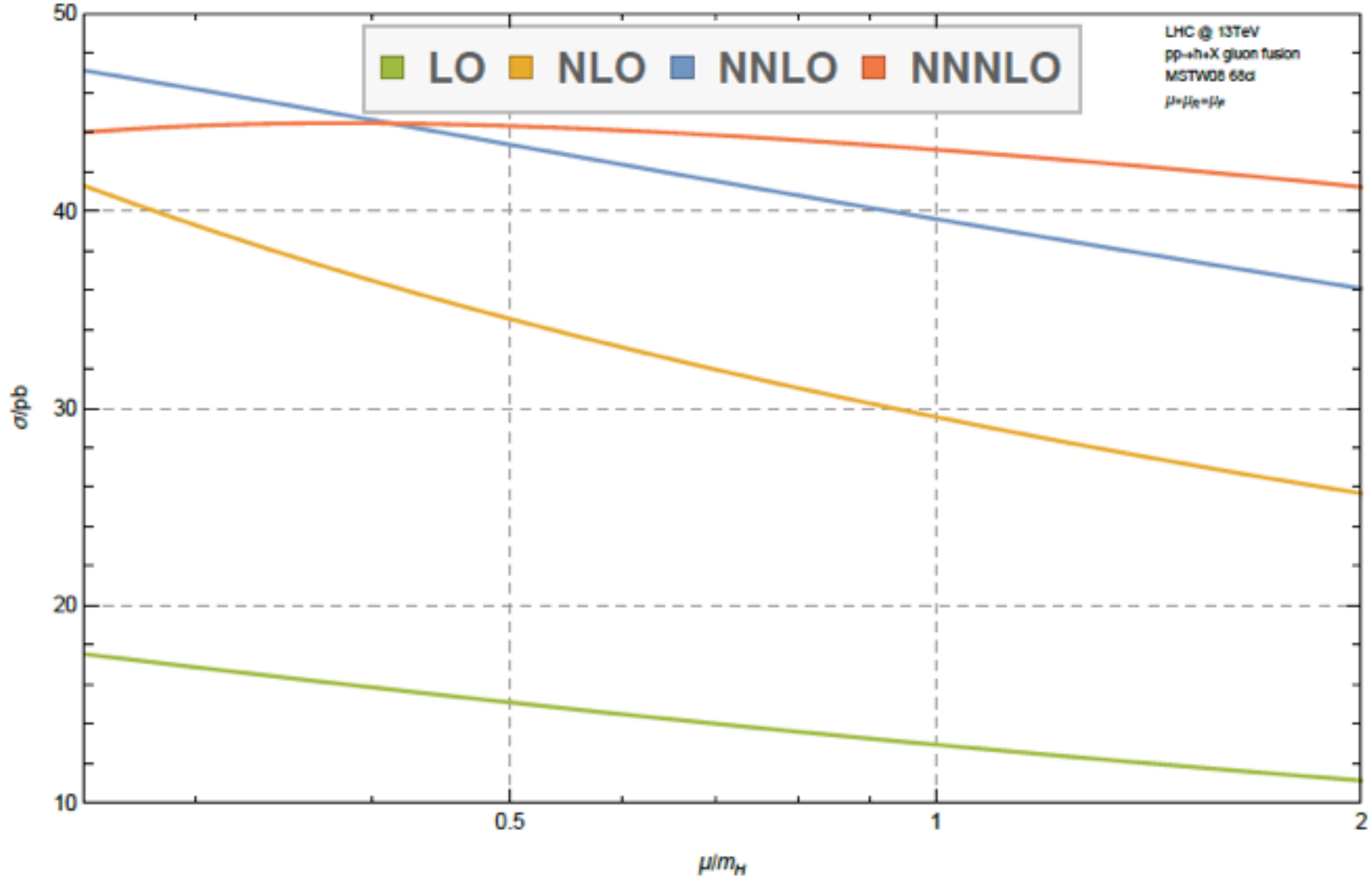


Keith Ellis
Fermilab

A world created with us in mind

- The most significant result of Run I of the LHC is the discovery of the Higgs boson in 2012
- Higgs boson (produced predominantly by gluon fusion) radiates copiously, thus emphasizing the importance of radiative corrections.
- Our field is front and centre in the physics program of run II.
- "With data taken in coming years at or near to the design energy of 14 TeV, a broader picture of physics at the TeV scale will emerge with implications for the future of the energy frontier program. Amongst the essential inputs will be precision measurements of the properties of the Higgs boson and direct searches for new physics that will make significant inroads into new territory." ATLAS Physics at High Luminosity, 1307.7292

Higgs total cross section at N^3LO



- σ= 44.31+0.31%-2.64%pb for $\mu \in [m_H/4, m_H]$

1503.06056,1505.04110 Duhr, Furlan,Mistlberger

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Uncertainty budget for gg→H

- Scale uncertainty negligible compared to PDF + α_S uncertainties at N3LO. Duhr

Huston

A comparison of ggF at NNLO

	CT14	MMHT2014	NNPDF3.0
scale = m_H			
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.

Most studies of the expected evolution of the gluon distribution uncertainty are targeted at higher x, so no statement yet on future evolution

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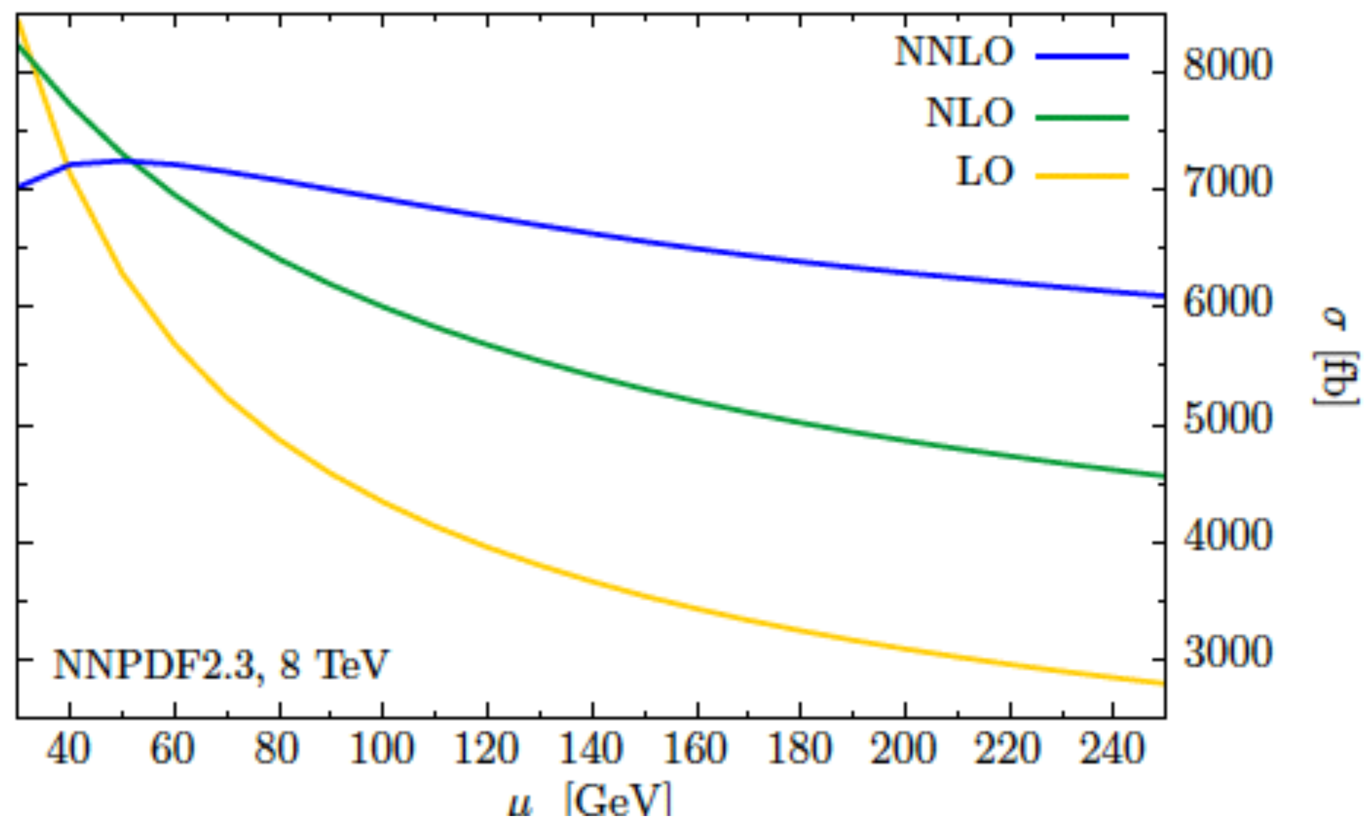
Higgs+1 jet

- σ=17.5+1.1-1.4pb
- QCD corrections depend on the kinematics, (K-factor dependent on p_T cut)
- Results for pure glue from Jaquier
- We look forward to a detailed comparison of the two (three) results

Boughezal et al,1504.07922, 1505.03893

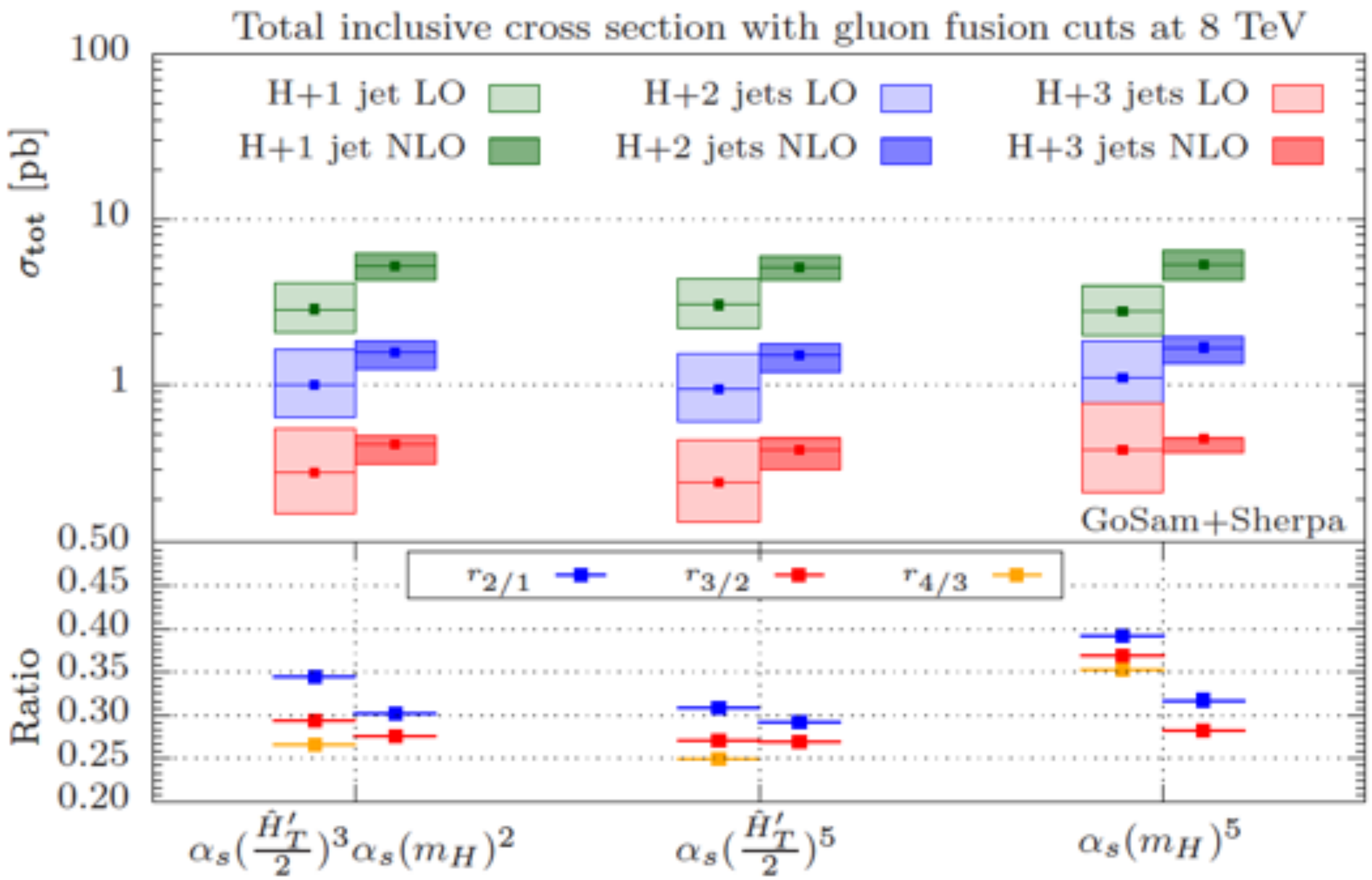


At 13 TeV

Process	α_s^2	α_s^3	α_s^4	α_s^5
$\sigma(pp \to H)$ pb [1]	13	30	40	43
$\sigma(pp \to H+$ jet) pb[2]		10	15	18
$\sigma(pp \to H+$ 2 jet) pb[3]			3.5	5.1
$\sigma(pp \to H+$ 3 jet) pb[3]				1.6

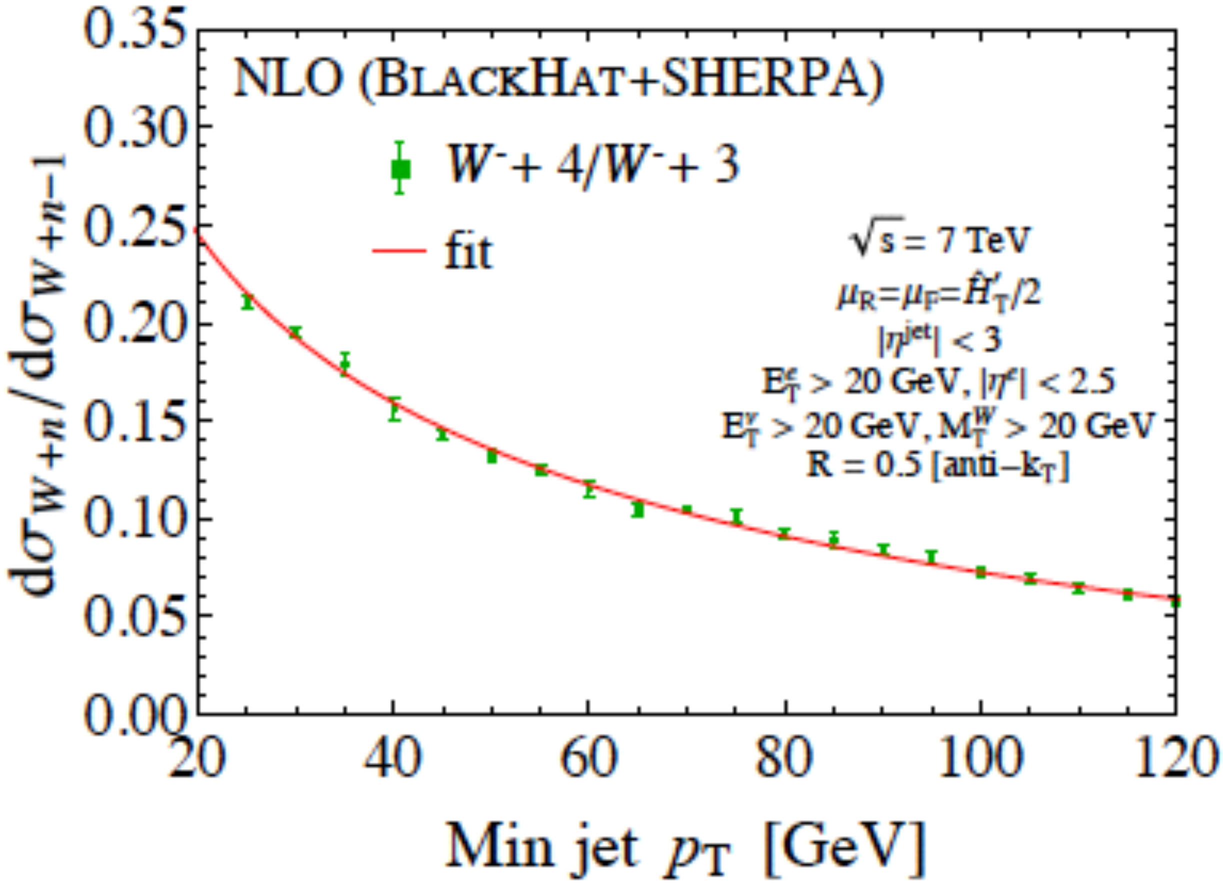
+ O(α_s^6) results from Greiner here

Propensity to radiate



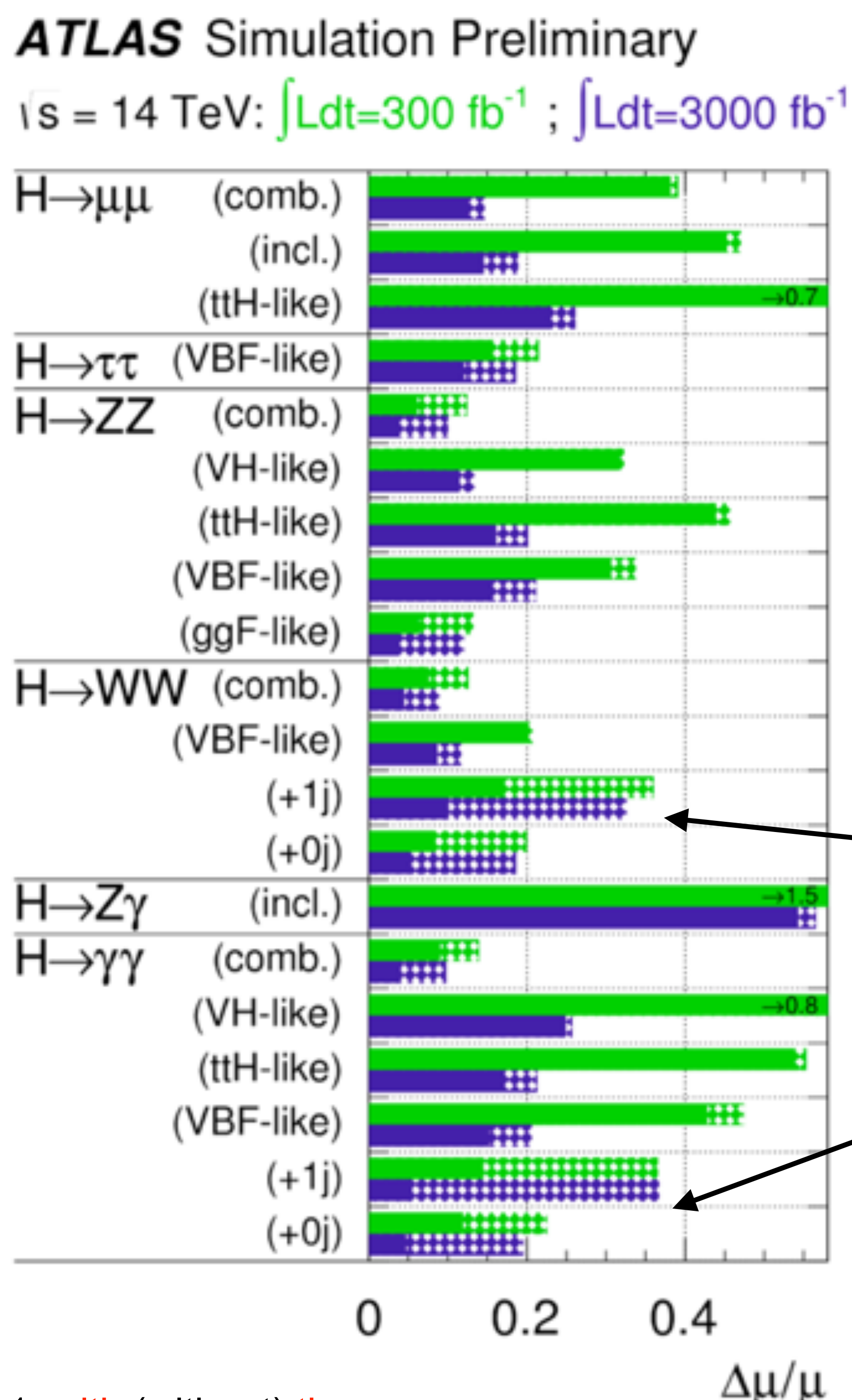
Greiner

Berends-Giele ratio greater for Higgs than for W



Influence of theory on signal strengths

ATL-PHYS-PUB-2013-014



Already impact here

ATLAS: Syst. errors as run 1, with (without) theory errors

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Our efforts are appreciated.

Legacy: Experiment – Theory Feedback

- Many many new MC Tools and calculations motivated by LHC Higgs experimental results:
    - Higgs production has largest LO→NLO→NNLO corrections of all LHC processes
    - Use of NLO MC popularized with Higgs @ LHC (eg. POWHEG, MC@NLO)
    - Fully NLO + extra parton now being commissioned for CMS : aMC@NLO

Si Xie

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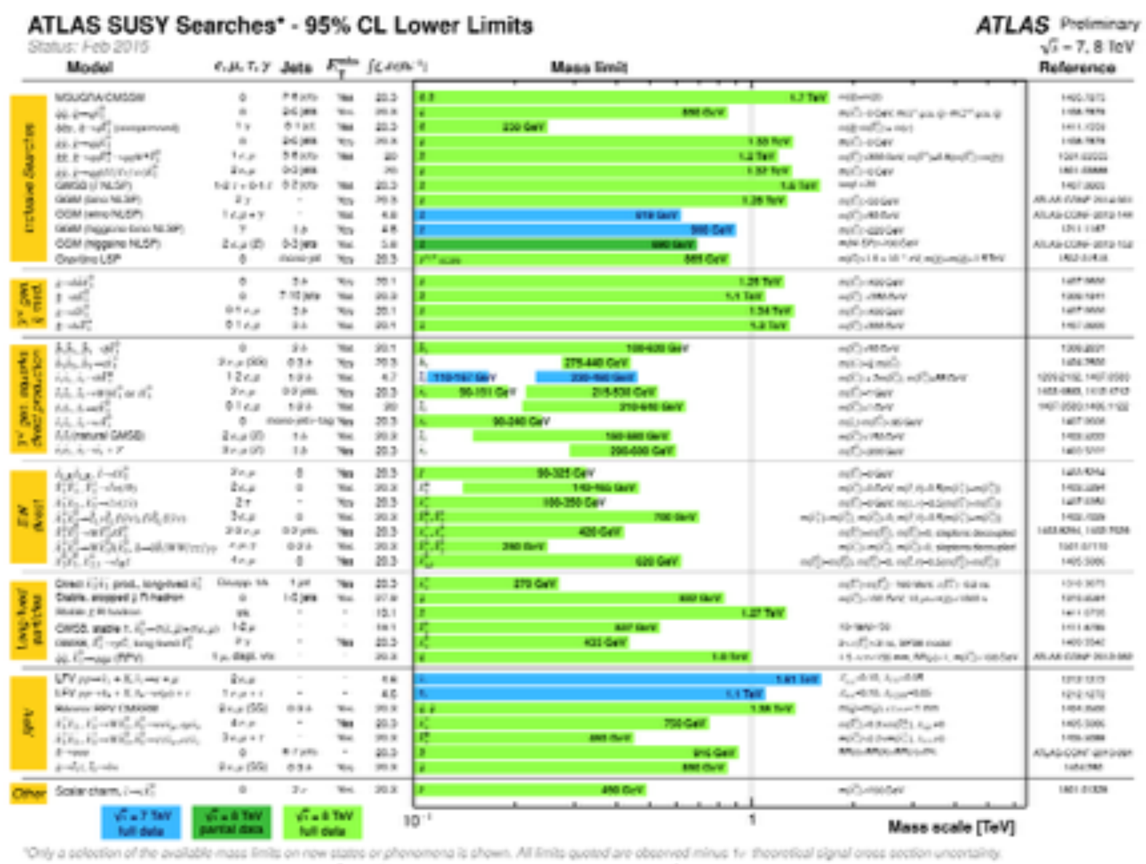
Superb background modeling

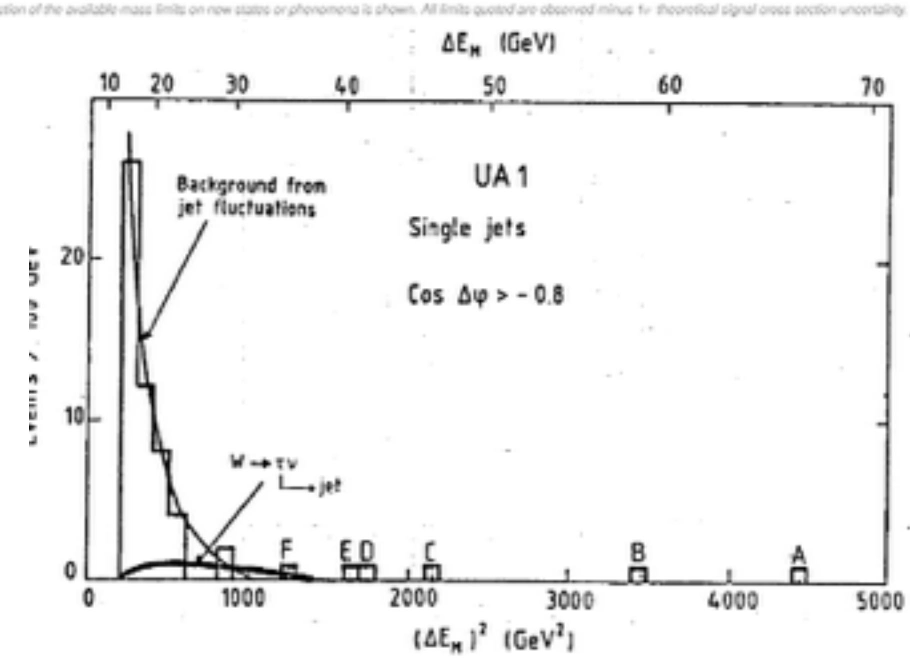
- Despite theoretical problems with the standard model there is no convincing evidence for physics beyond the standard model

- Here too, our community has contributed in a significant way.

- The reliable modeling of backgrounds has aided the conduct of BSM searches.

- Very few false positives, c.f. the monojets in 1984.





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NNLO

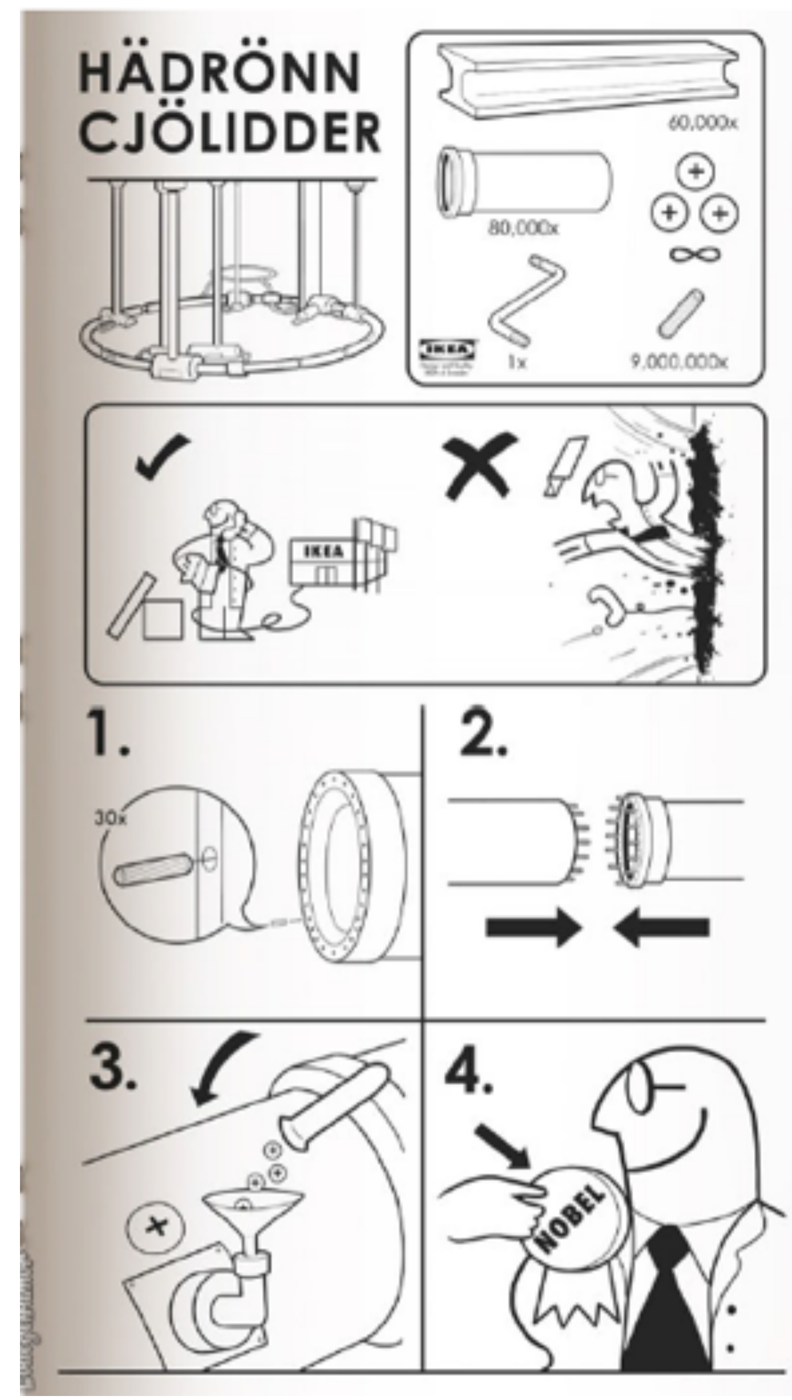
- ~25% of the contributions to this conference dealt with NNLO calculations, in one way or another.
- NNLO calculations roughly at the level of NLO in 1990.
  - NLO 2 to 2 virtual matrix elements known
  - NLO top cross section (total and differential) known
  - NLO 2 to 3 calculations just beginning to be tackled?
- Will we make faster progress on NNLO?

NNLO - 2 loop matrix elements

- Tremendous advance in analytical methods
- differential equations, canonical basis, coproduct augmented symbol calculus
- 2→2 processes with four independent scales seem to be within reach, but extension to 2→3 processes, eg $gg \to V_1 V_2 g$ seems out of reach. (Tancredi).
- If 2→3 represents a wall, then we need to investigate other methods.
- The investment in numerical methods compared to analytic methods, seems to me to be too small.
  - Contour deformation in FP space, sector decomposition Schlenk
  - Contour deformation in momentum space, e.g. Becker, Weinzierl 1211.0509

NNLO-some assembly required

- Contributions from RR, RV and VV.
- For the lower multiplicities the poles are explicit, whereas as for higher multiplicities, they appear after integration.
- Thus the requirement to cancel the poles appears to be in contradiction with the desire for a differential cross section.
- Four main methods



Antenna subtraction

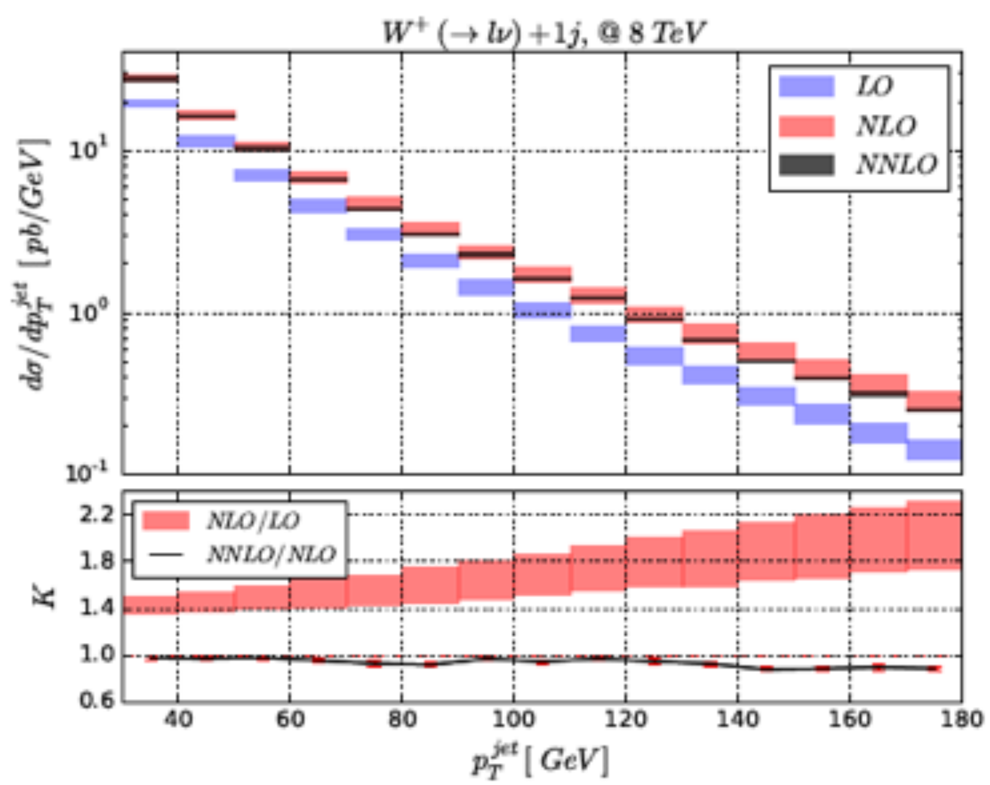
- Proposal for NNLO, Gehrmann-De Ridder, Gehrmann,Glover hep/ph-0505111
- Application to e+e- -> 3 jets Gehrmann-De Ridder, Gehrmann,Glover, Heinrich 0707.1285
- Dijet production
    - Quark-antiquark at leading color Currie, Glover,Wells 1301.4693
    - Leading color, only gluons Gehrmann-DeR, Gehrmann, Glover, Pires 1301.7310
    - Full color, only gluons Gehrmann-DeR, Gehrmann, Glover, Pires 1301.3993Dijet production
- Higgs+jet (gluons) Chen Gehrmann, Glover, Jacquier
- Top-pair production (quark-antiquark only) Abelof, Gehrmann-DeR 1409.3148

qT subtraction

- Based on transverse momentum resummation formula of Catani-Grazzini
- Originally for Higgs hep/ph 0703012
- W,Z production Catani,Cieri,Ferrera,DiFlorian Grazzini ,0903.2120
- γ-γ Catani,Cieri,de Florian,Ferrera,Grazzini 1110.2375
- WH Ferrera, Grazzini,Tramontano 1312.1669
- Zγ Grazzini,Kallweit,Rathlev,Torre 1309.7000
- ZZ Cascioli, Gehrmann,Grazzini,Kallweit,Maierhoeffer,von Manteuffel, Pozzorini,Rathlev,Tancredi,Weihs 1405.2219
- ZH Ferrera,Grazzini,Tramontano 1407.4747
- WW Gehrmann,Grazzini,Kallweit,vonManteuffel, Pozzorini, Rathlev,Tancredi 1408.5243
- Wγ,Zγ, Grazzini, Kallweit, Rathlev, 1504.01330

N-jettiness method

- New method similar in style to q_T subtraction, but applicable to colored final states.
- W+jet, Boughezal, Foecke, Liu, Petriello 1504.02131
- Higgs+jet, Boughezal, Foecke, Giele, Liu, Petriello 1505.03893
- Higgs,Z- Gaunt,Stahlhofen,Tackmann,Walsh 1505.04794
- Tremendous increase in computer power has made subtraction style methods feasible.



N-jettiness slicing or subtraction?

- Name may be inherited from q_T subtraction.
- At its core it is a slicing method.
  - Caveat I: Above the cut for NLO, at least in MCFM (a subtraction method) has been used.
  - Caveat II: It is possible to tweak the method, so that there is a subtraction local in τ_N, but not in the other phase space variables.

For NNLO:

$$\sigma(X) = \int_0^{\mathcal{T}_\delta} \mathrm{d}\mathcal{T}_N \frac{\mathrm{d}\sigma(X)}{\mathrm{d}\mathcal{T}_N} + \int_{\mathcal{T}_\delta} \mathrm{d}\mathcal{T}_N \frac{\mathrm{d}\sigma(X)}{\mathrm{d}\mathcal{T}_N}$$
$$= \sigma^{\mathrm{sing}}(X, \mathcal{T}_\delta) + \int_{\mathcal{T}_\delta} \mathrm{d}\mathcal{T}_N \frac{\mathrm{d}\sigma(X)}{\mathrm{d}\mathcal{T}_N} + \mathcal{O}(\delta_{\mathrm{IR}})$$

Below the cut: analytic result for N jet cross section

Above the cut NLO N+1jet

Gaunt, Stahlhofen, Tackmann and Walsh

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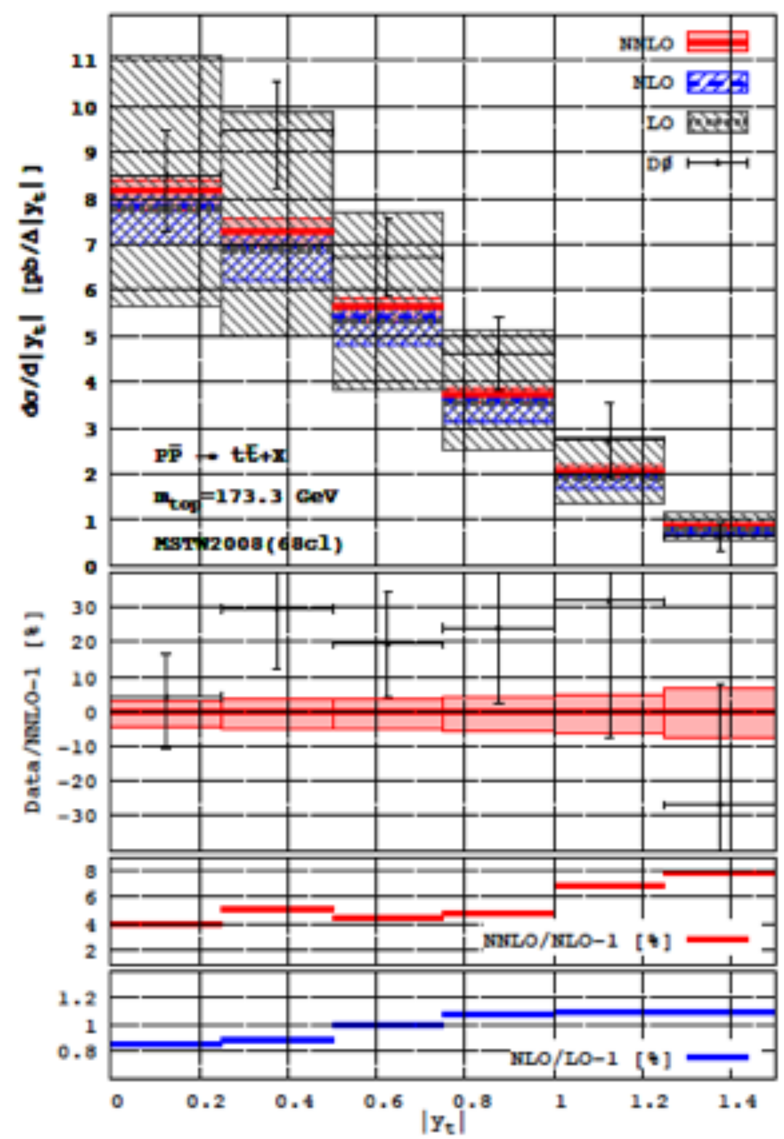
Sector-improved Residue subtraction scheme

- Invented in its current form by Czakon 1005.0274
- $Z \to e^+e^-$ 1111.7041
- top quark decay 1301.7133
- $b \to X e \nu$ 1302.0444
- Single top production 1404.7116
- Muon decay asymmetry 1403.3386
- H+jet 1302.6216, 1504.07933
- Total cross sections for ttbar,1303.6254
- Differential top pair production,1411.3007

Czakon



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NNLO - some assembly required

- Antenna
  - Pros:Analytic cancellation of poles, demonstrated for 2->2 colored scattering
  - Con: More challenging interface to existing NLO codes
- Sector improved residue subtraction scheme.
  - Pros:Brute force method, offers possibility of generalization to arbitrary processes, demonstrated for 2->2 colored scattering
  - Con: Numerical cancellation of poles
- qt/N-jettiness subtraction
  - Pro:Meshes well with existing NLO codes
  - Con:Slicing method, have to demonstrate independence from cutoff parameter.
- Colour subtraction
  - Pro:Local subtraction terms
  - Con: No NNLO application to processes with initial state hadrons yet.

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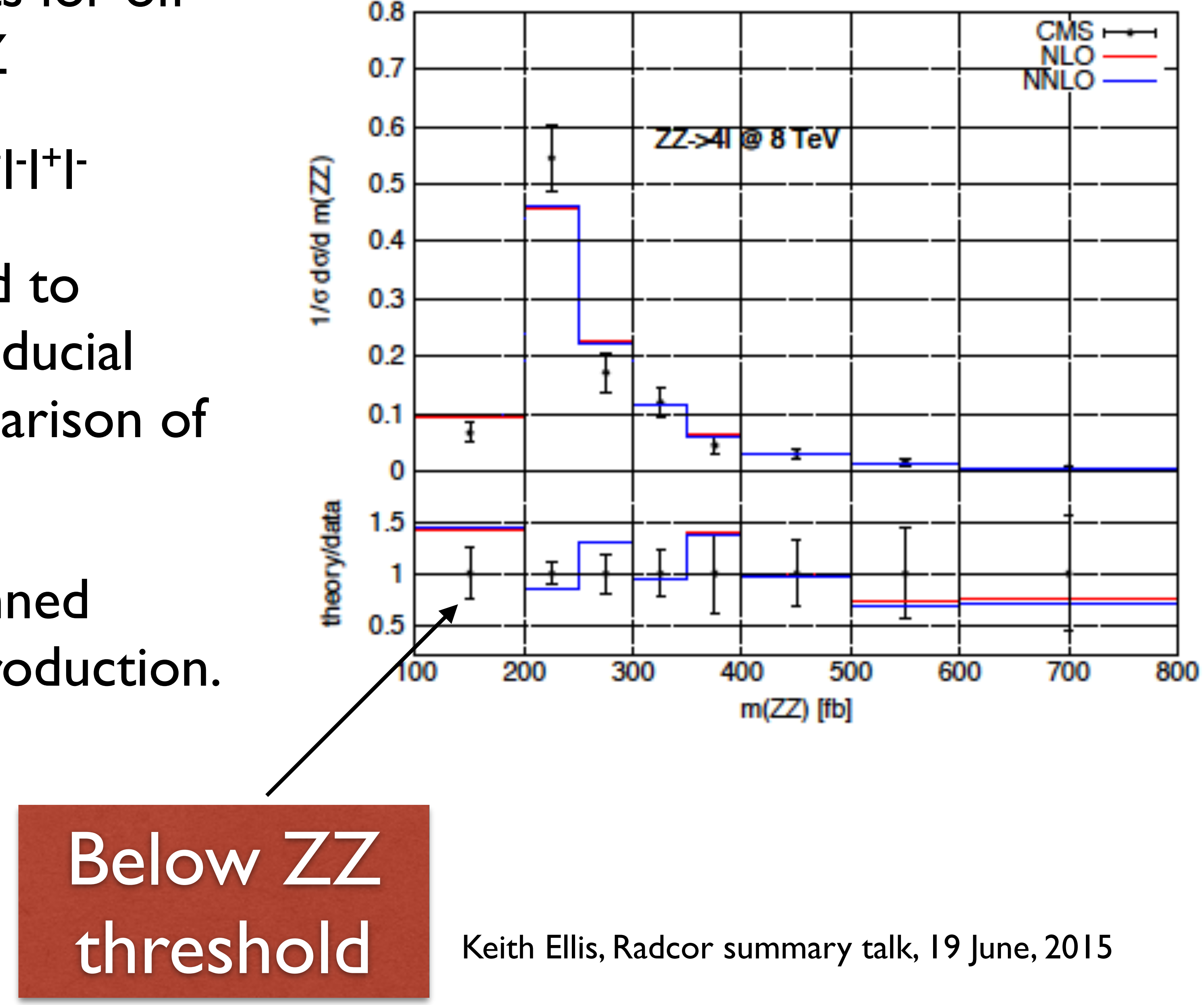
NNLO new-new results

- preliminary results for off-shell effects in ZZ
- $pp \to Z/\gamma + Z/\gamma \to l^+l^-l^+l^-$
- data is normalized to cross-section in fiducial region, so a comparison of shape only.
- we await finer binned results on ZZ* production.

Grazzini,Kallweit,Rathlev
+VV' matrix elements from
Tancredi,von Manteuffel….

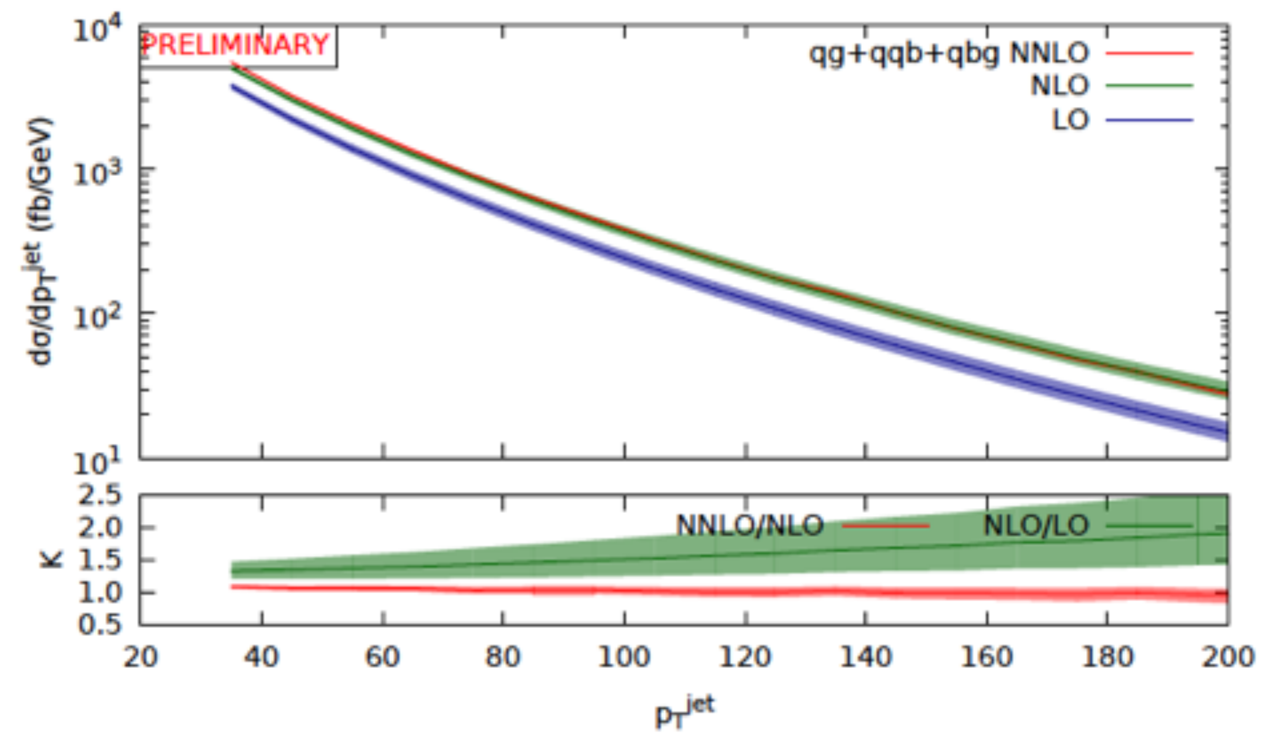


NNLO new-new results:Z+1jet

- Preliminary results for blue channels

Morgan

Initial state	σ (pb)	% contribution
qg	80.2	55.6%
$q\bar{q}$	33.1	22.9%
$\bar{q}g$	33.1	22.9%
gg	-4.0	-2.7%
qq	1.8	1.2%
$\bar{q}\bar{q}$	0.1	0.1%
Total	144.3	100.0%



- Missing channels can still have significant effects on details of differential distributions.

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Wish-listeria I

Process	State of the Art	Desired	Delivered
H	dσ @ NNLO QCD (expansion in $1/m_t$) full m_t/m_b dependence @ NLO QCD and @ NLO EW NNLO+PS, in the $m_t \to \infty$ limit	dσ @ NNNLO QCD (infinite-m_t limit) full m_t/m_b dependence @ NNLO QCD and @ NNLO QCD+EW NNLO+PS with finite top quark mass effects	1503.06056[2] 1309.0017[3], 1501.04637[4] 1407.3773[5]
H + j	dσ @ NNLO QCD (g only) and finite-quark-mass effects @ LO QCD and LO EW	dσ @ NNLO QCD (infinite-m_t limit) and finite-quark-mass effects @ NLO QCD and NLO EW	1408.5325[6],1504.07922[7],1505.03893[8]
H + 2j	σ_{tot}(VBF) @ NNLO(DIS) QCD dσ(VBF) @ NLO EW dσ(gg) @ NLO QCD (infinite-m_t limit) and finite-quark-mass effects @ LO QCD	dσ(VBF) @ NNLO QCD + NLO EW dσ(gg) @ NNLO QCD (infinite-m_t limit) and finite-quark-mass effects @ NLO QCD and NLO EW	1506.02660[9]
H + V	dσ @ NNLO QCD dσ @ NLO EW σ_{tot}(gg) @ NLO QCD (infinite-m_t limit)	with $H \to b\bar{b}$ @ same accuracy dσ(gg) @ NLO QCD with full m_t/m_b dependence	1501.07226[10]
tH and $\bar{t}$H	dσ(stable top) @ LO QCD	dσ(top decays) @ NLO QCD and NLO EW	
$t\bar{t}$H	dσ(stable tops) @ NLO QCD	dσ(top decays) @ NLO QCD and NLO EW	1407.0823[11]
$gg \to HH$	dσ @ NLO QCD (leading m_t dependence) dσ @ NNLO QCD (infinite-m_t limit)	dσ @ NLO QCD with full m_t/m_b dependence	1408.2422[12, 13]

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Wish-listeria II

Process	State of the Art	Desired	Delivered
$t\bar{t}$	$\sigma_{\rm tot}$(stable tops) @ NNLO QCD $d\sigma$(top decays) @ NLO QCD $d\sigma$(stable tops) @ NLO EW	$d\sigma$(top decays) @ NNLO QCD + NLO EW	1411.3007[15]
$t\bar{t} + j(j)$	$d\sigma$(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	1404.7116[16]
dijet	$d\sigma$ @ NNLO QCD (g only) $d\sigma$ @ NLO EW (weak)	$d\sigma$ @ NNLO QCD + NLO EW	1412.3427[17], 15xx.xxxx
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	

Wish-listeria III

Process	State of the Art	Desired	Delivered
V	$d\sigma$(lept. V decay) @ NNLO QCD $d\sigma$(lept. V decay) @ NLO EW	$d\sigma$(lept. V decay) @ NNNLO QCD and @ NNLO QCD+EW NNLO+PS	1407.2940[18]
V + j(j)	$d\sigma$(lept. V decay) @ NLO QCD $d\sigma$(lept. V decay) @ NLO EW	$d\sigma$(lept. V decay) @ NNLO QCD + NLO EW	1504.02131[10]
VV′	$d\sigma$(V decays) @ NLO QCD $d\sigma$(on-shell V decays) @ NLO EW	$d\sigma$(decaying off-shell V) @ NNLO QCD + NLO EW	1309.7000[19], 1405.2219[20],1408.5243[21], 1504.01330[22]
$gg \to VV$	$d\sigma$(V decays) @ LO QCD	$d\sigma$(V decays) @ NLO QCD	
$V\gamma$	$d\sigma$(V decay) @ NLO QCD $d\sigma$(PA, V decay) @ NLO EW	$d\sigma$(V decay) @ NNLO QCD + NLO EW	
$Vb\bar{b}$	$d\sigma$(lept. V decay) @ NLO QCD massive b	$d\sigma$(lept. V decay) @ NNLO QCD + NLO EW, massless b	
$VV'\gamma$	$d\sigma$(V decays) @ NLO QCD	$d\sigma$(V decays) @ NLO QCD + NLO EW	
$VV'V''$	$d\sigma$(V decays) @ NLO QCD	$d\sigma$(V decays) @ NLO QCD + NLO EW	
VV′ + j	$d\sigma$(V decays) @ NLO QCD	$d\sigma$(V decays) @ NLO QCD + NLO EW	
VV′ + jj	$d\sigma$(V decays) @ NLO QCD	$d\sigma$(V decays) @ NLO QCD + NLO EW	
$\gamma\gamma$	$d\sigma$ @ NNLO QCD + NLO EW	q_T resummation at NNLL matched to NNLO	1505.03162[23]

Considerable amount of red ink since mid 2014!

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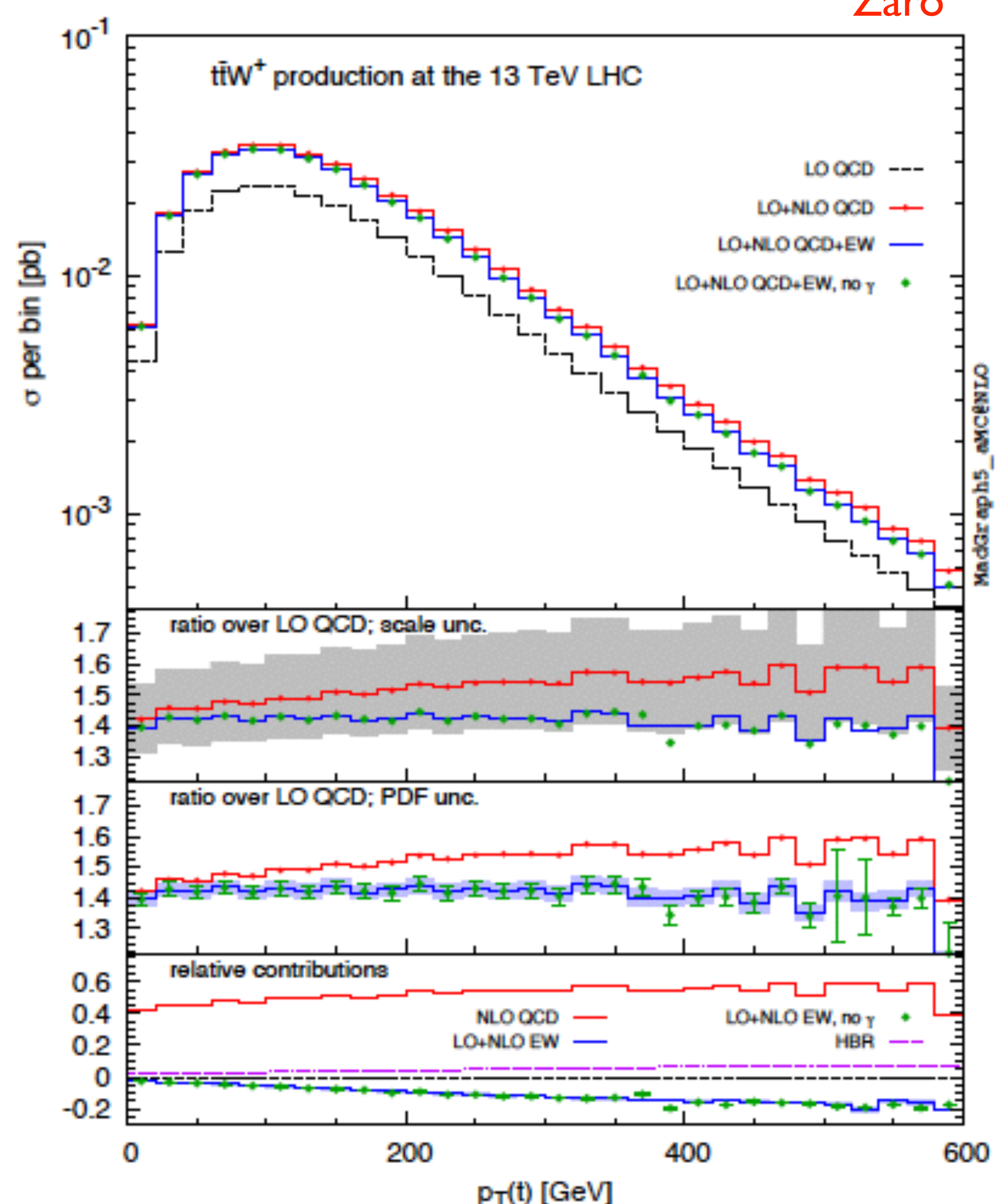
Electroweak corrections.

- Similar size as NNLO, $\alpha \approx \alpha_S^2$, except at high energy.
- Full calculation of $O(\alpha\alpha_S)$ corrections to Drell Yan, determines correct strategy for inclusion of electroweak corrections for W mass measurement (Dittmaier, Huss).
- Initial steps in automatic NLO electroweak corrections, eg ttW.

Zaro



Electroweak corrections

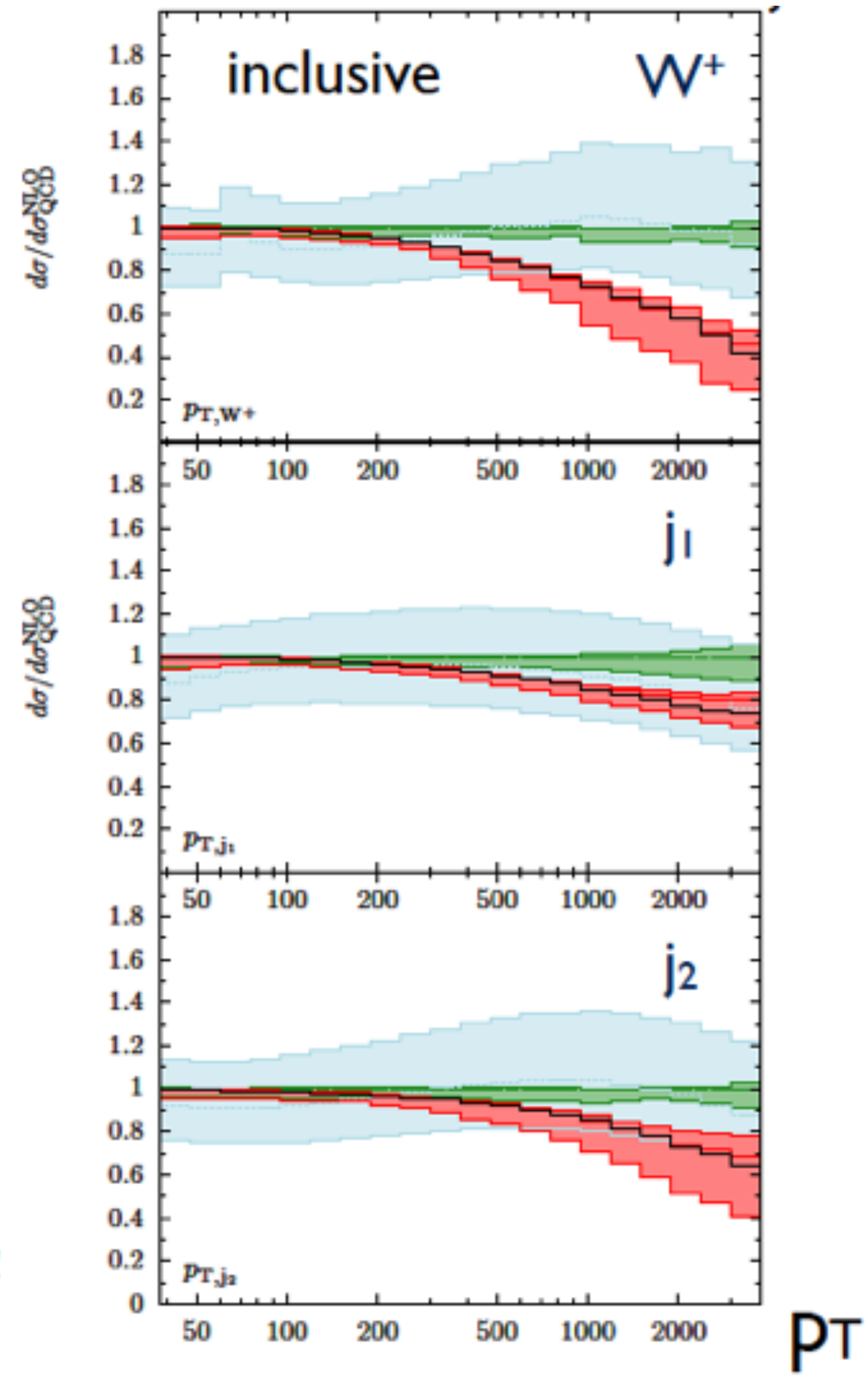
- Electroweak effects calculated with Openloops.
- W+1 jets giant QCD K-factors at large p_T (quark-quark scattering configurations).
- W+2 jets large electroweak corrections at large P_T

EW corrections

- **Sudakov behaviour** in all p_T tails:
  - -30–60% for W-boson at 1-4 TeV
  - -15–25% for 1st and 2nd jet at 1-4 TeV

different!

Lindert



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- Almost all work on NLO is of an automatized nature
- Non-automatic work is of a niche nature,
  - stable input for NNLO (W^+W^-+jet Robens)
  - learning exercises for two loop ($H\rightarrow Z\gamma$, Kara)

Madgraph5_amc@nlo

- Madgraph5_amc@nlo now able to handle processes that start at loop level (Hirschi).

Process Single boson + jets		Syntax	Cross section (pb) $\sqrt{s} = 13$ TeV	$\Delta_{\hat{\mu}}$	Δ_{PDF}
a.1	$pp \to H$	`p p > h [QCD]`	17.79 ± 0.060	$^{+31.3\%}_{-23.1\%}$	$^{+0.5\%}_{-0.9\%}$
a.2	$pp \to Hj$	`p p > h j [QCD]`	12.86 ± 0.030	$^{+42.3\%}_{-27.7\%}$	$^{+0.6\%}_{-0.9\%}$
a.3	$pp \to Hjj$	`p p > h j j QED=1 [QCD]`	6.175 ± 0.020	$^{+61.8\%}_{-35.6\%}$	$^{+0.7\%}_{-0.9\%}$
*a.4	$gg \to Zg$	`g g > z g [QCD]`	43.05 ± 0.060	$^{+43.7\%}_{-28.4\%}$	$^{+0.7\%}_{-1.0\%}$
†a.5	$gg \to Zgg$	`g g > z g g [QCD]`	20.85 ± 0.030	$^{+64.5\%}_{-36.5\%}$	$^{+1.0\%}_{-1.1\%}$
†a.6	$gg \to \gamma g$	`g g > a g [QCD]`	75.61 ± 0.200	$^{+73.8\%}_{-41.6\%}$	$^{+0.7\%}_{-1.1\%}$
†a.7	$gg \to \gamma gg$	`g g > a g g [QCD]`	14.50 ± 0.030	$^{+76.2\%}_{-40.7\%}$	$^{+0.6\%}_{-1.0\%}$

Recola

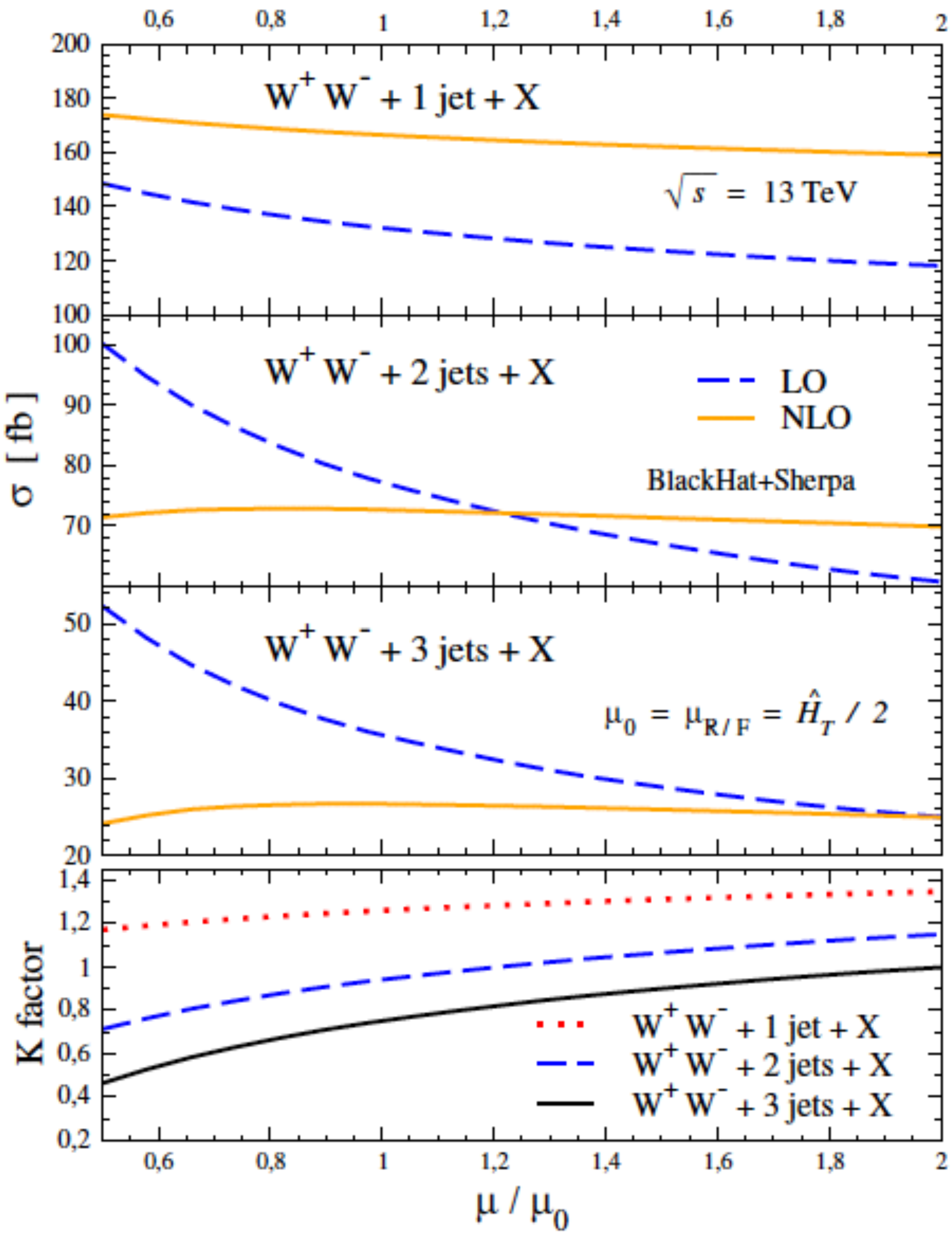
- Recursive calculation of one loop amplitudes (based on off-shell recursion) (Uccirati).

Features of RECOLA

- Full Standard Model in the complex mass scheme
- Mass and dimensional regularization for collinear and soft singularities
- Dynamical running of α_s
- Numerical check of cancellation of UV divergences

- Relies on Collier library of one loop integrals (Hofer).

Scale sensitivity for W+W- + 1,2,3 jets



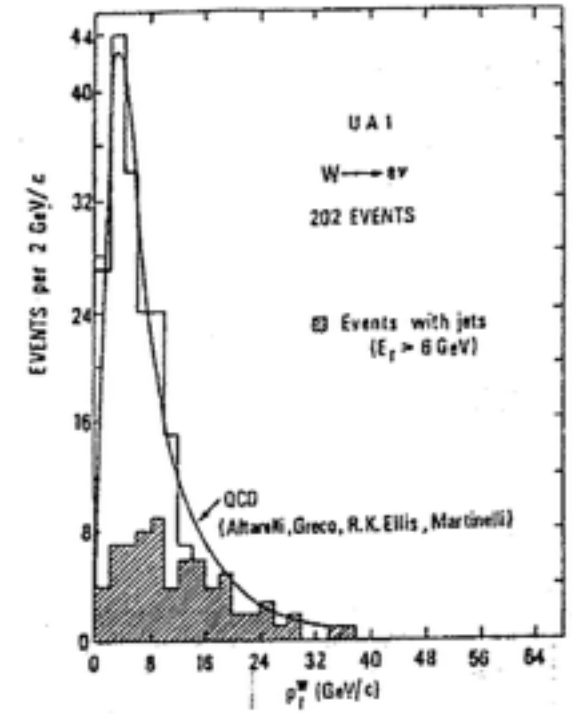
Febres Cordero

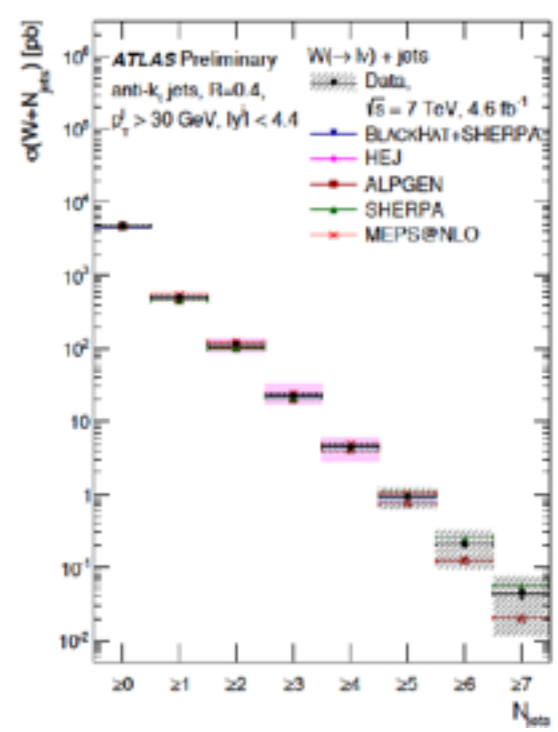
- Total cross sections as function of unphysical scales
- W^+W^-+0 Jet not shown (corrections very large, NNLO needed → (See D. Rathlev's talk!)
- Small scale sensitivity at NLO
- Large multiplicity needs NLO

PRELIMINARY

Caveat emptor

- The summarizer's job is hard, but the progress has been rapid
- It is a great time to work on radiative correction
- Tough challenges, great tools and great rewards
- Many thanks to Zvi, Harald Ita, Scott Davies…





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