# Hard QCD
# — theoretical aspects —

Giulia Zanderighi

Oxford University & STFC

Perugia, 11 June 2011

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*that are relevant for Tevatron and LHC data interpretation*

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# Present status

Atlas and CMS have collected already around 45pb$^{-1}$ (700 pb$^{-1}$) very high quality data at $\sqrt{s}$ = 7 TeV in 2010 (2011)

The 2010 data have been used for commissioning and calibration, with performances close to the TDR specifications

|\sum_{i\in all particles observed} \vec p_{ti}|

At the LHC all major Standard Model processes have already been re-established
(inclusive jet, inclusive photon, charged hadrons, heavy-mesons, electroweak and top processes, single top, di-bosons ... )

We are entering a new territory in new-physics searches with sensitivities already exceeding those of LEP and Tevatron
(Higgs, SUSY, Heavy bosons W' and Z', leptoquarks, long-lived particles ... )

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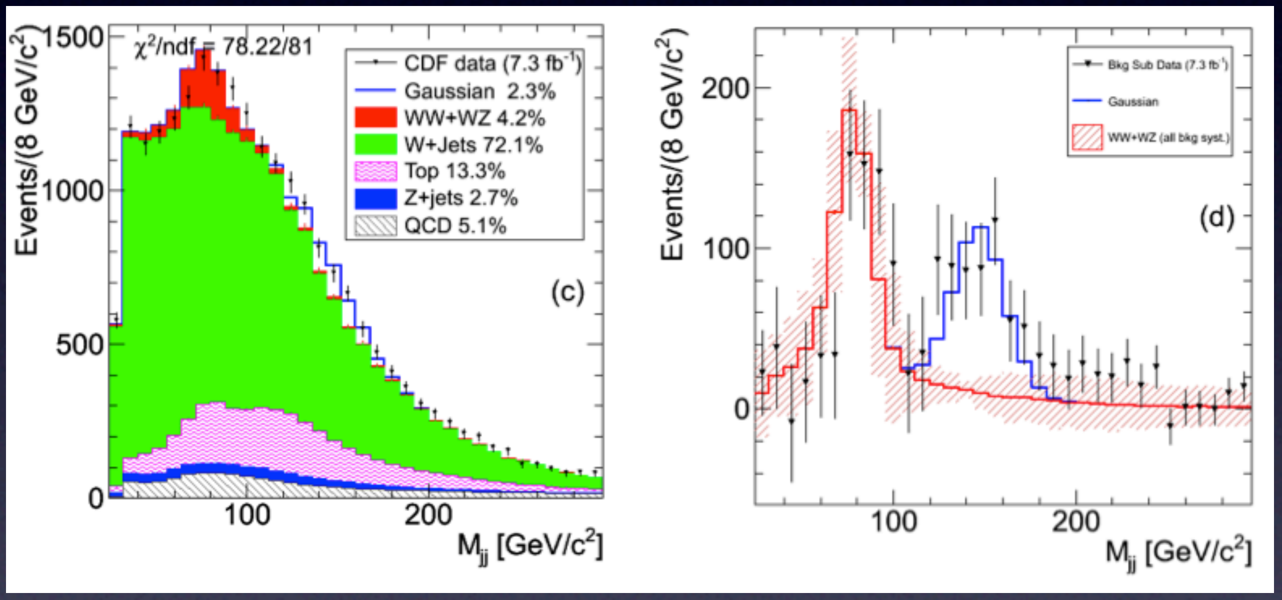
At the LHC, no matter what physics you do, QCD will be part of your life

# Wjj excess

CDF sees a peak in $m_{jj}$ for W + dijet events: first claim 3.2 σ [4.3$fb^{-1}$]

CDF -- PRL106, 171801 2011

Update to include 7.3$fb^{-1}$ ⇒ more than 4 σ




http://www-cdf.fnal.gov/physics/ewk/2011/wjj/7_3.html

Since then

- a larger numbers of tentative BSM explanations
- three SM analysis

[ ... ]

Plehn et al. 1104.4087; Sullivan & Menon 1104.3790; Campbell et al. 1105.4594

Best possible SM predictions and solid BSM predictions very helpful.
At the LHC expect many similar cases.

# Toolkit

- Parton shower (PS) [e.g. Pythia, Herwig, Ariadne, ... ]
- Matrix elements (ME) generators, usually + PS [e.g. Alpgen, Helac, Madgraph, Sherpa .... ]

- NLO [e.g. NLOjet++, MCFM, DYRAD, VecBos ...]
- NLO+ PS [(a)MC@NLO and POWHEG]
- NLO + NLL (NNLL) analy. resummations [ResBos, many predictions, mostly observable specific, sometimes from effective theories]

- NLO QCD+EW [RGHiggs, various calculations ... ]

➠ talks of R. Boughezal, F. Petriello, F. Piccinini

- approx. NNLO [e.g. tt ... ]
- inclusive NNLO
- exclusive NNLO with flexible cuts [FEHIP, H@NNLO, FEWZ, DY@NNLO]
- NNLO + NNLL analy. resummations [e.g. thrust in $e^+e^- \to$ 3jets ... ]
- ...

more difficult

available for lower multiplicities

# Monte Carlos

Essentially every LHC analysis will make use of one or more Monte Carlo simulation for

- the signal
- the background
- underlying event / non-perturbative corrections
- pile-up
- efficiency studies / detector response

Yet, level of sophistication is such that today almost no study uses "just Pythia/Herwig". To describe hard QCD radiation need, at least, exact matrix elements [Madgraph/Sherpa/Alpgen...]

# P.S./M.E.

Recent progress in PS/ME includes

- Pythia (8.1): new $p_t$-ordered shower + sophisticated MPI
- Herwig++ (2.4): updated angular-ordered shower, default includes now multiple interaction model
- Sherpa (1.3): dipole shower, efficient multi-leg M.E. (Comix) via CKKW matching
- Madgraph (5.0): automated HELAS routines, more extended spin and color support, increased speed and stability, unlimited decay chain . . .

Continuous progress in various directions

These codes will undergo stress-test in the coming years

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Revolutionary ideas

- sew together tree level amplitudes to compute loop amplitudes [on-shell intermediate states, cuts, unitarity ideas ... ]
- OPP: extract coefficients of master integrals by evaluating the amplitudes at specific values of the loop momentum [algebraic method]
- full D-dimensional unitarity as a practical numerical tool

Bern, Dixon, Kosower; Britto, Cachazo, Feng; Ossola, Pittau, Papadopoulos; Ellis, Giele, Kunszt, Melnikov

For a pedagogical review on unitarity methods see Ellis, Kunszt, Melnikov, GZ '11

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[W/Z+3jets, WW + 2jets, tt +2jets, tt+bb, ee $\rightarrow$ 5jets]

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Feynman diagram methods have also been applied successfully to 2 → 4 calculations
[NB: only few years ago this was considered impossible]

[WWbb, tt+bb, bbbb]

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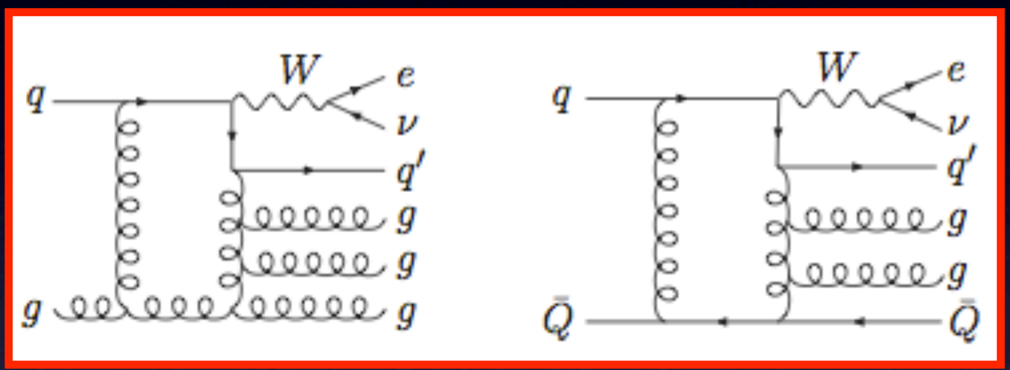
[WWbb, tt+bb, bbbb]

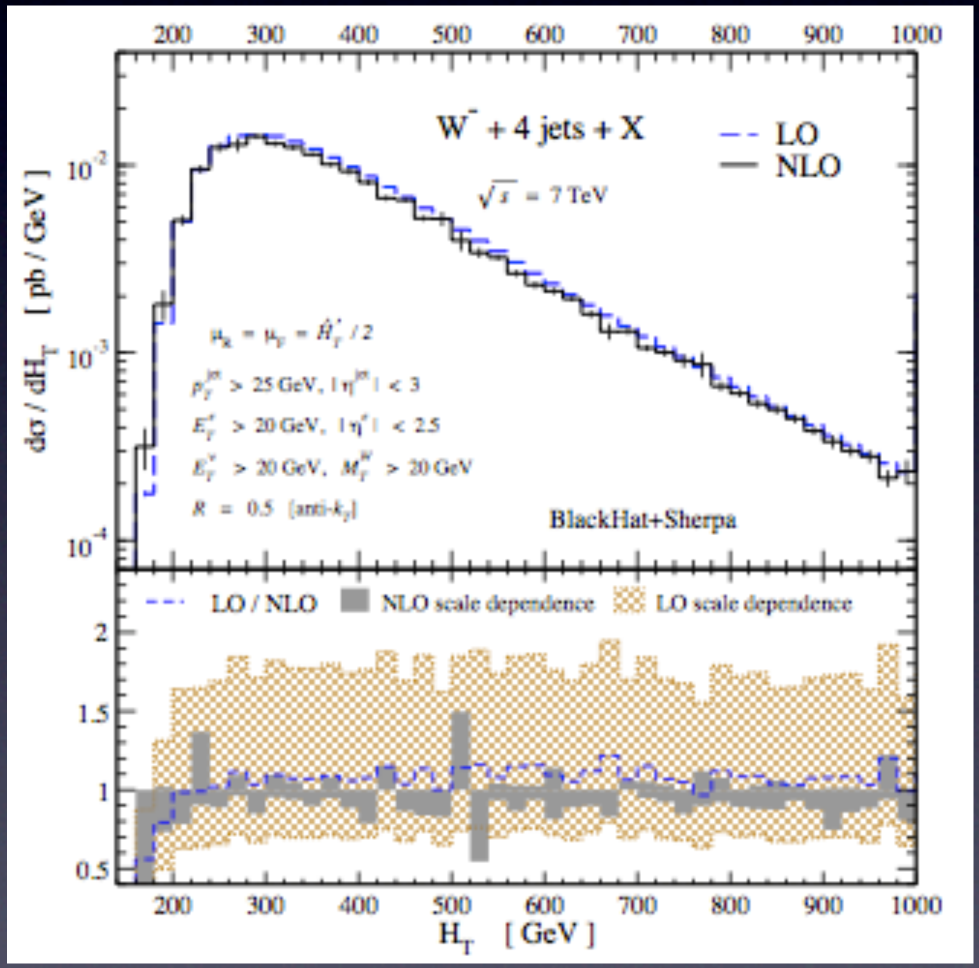
*The revolution is not yet in the applications that we see today, rather in the prospect for low-cost computer automated NLO calculations even beyond 2 → 4 in the near future*

# W + 4jets at NLO

Berger et al.'10

Sample diagrams:




$$H_T = \sum_j p_{T,j} + p_{T,e} + p_{T,miss}$$

- First pp → 5
- Expected reduction of theoretical uncertainties
- Z + 4 jets in progress

(*) Leading color calculation (OK to within 3% for lower multiplicities) + solid theoretical arguments; missing W+6q (also small)

# Automation of NLO

Hirschi et al. 1103.0621

General approach based on

- Feynman diagrams (limited to relatively low multiplicities)
- OPP procedure for virtual
- FKS subtraction of divergences
- clever and efficient procedure for instabilities

Improvements and refinements expected soon. No public code yet.

| | Process | $\mu$ | $n_{lf}$ | Cross section (pb) LO | Cross section (pb) NLO |
|---|---|---|---|---|---|
| a.1 | $pp \to t\bar{t}$ | $m_{top}$ | 5 | $123.76 \pm 0.05$ | $162.08 \pm 0.12$ |
| a.2 | $pp \to tj$ | $m_{top}$ | 5 | $34.78 \pm 0.03$ | $41.03 \pm 0.07$ |
| a.3 | $pp \to tjj$ | $m_{top}$ | 5 | $11.851 \pm 0.006$ | $13.71 \pm 0.02$ |
| a.4 | $pp \to t\bar{b}j$ | $m_{top}/4$ | 4 | $25.62 \pm 0.01$ | $30.96 \pm 0.06$ |
| a.5 | $pp \to t\bar{b}jj$ | $m_{top}/4$ | 4 | $8.195 \pm 0.002$ | $8.91 \pm 0.01$ |
| b.1 | $pp \to (W^+ \to)e^+\nu_e$ | $m_W$ | 5 | $5072.5 \pm 2.9$ | $6146.2 \pm 9.8$ |
| b.2 | $pp \to (W^+ \to)e^+\nu_e\, j$ | $m_W$ | 5 | $828.4 \pm 0.8$ | $1065.3 \pm 1.8$ |
| b.3 | $pp \to (W^+ \to)e^+\nu_e\, jj$ | $m_W$ | 5 | $298.8 \pm 0.4$ | $300.3 \pm 0.6$ |
| b.4 | $pp \to (\gamma^*/Z \to)e^+e^-$ | $m_Z$ | 5 | $1007.0 \pm 0.1$ | $1170.0 \pm 2.4$ |
| b.5 | $pp \to (\gamma^*/Z \to)e^+e^-\, j$ | $m_Z$ | 5 | $156.11 \pm 0.03$ | $203.0 \pm 0.2$ |
| b.6 | $pp \to (\gamma^*/Z \to)e^+e^-\, jj$ | $m_Z$ | 5 | $54.24 \pm 0.02$ | $56.69 \pm 0.07$ |
| c.1 | $pp \to (W^+ \to)e^+\nu_e b\bar{b}$ | $m_W + 2m_b$ | 4 | $11.557 \pm 0.005$ | $22.95 \pm 0.07$ |
| c.2 | $pp \to (W^+ \to)e^+\nu_e t\bar{t}$ | $m_W + 2m_{top}$ | 5 | $0.009415 \pm 0.000003$ | $0.01159 \pm 0.00001$ |
| c.3 | $pp \to (\gamma^*/Z \to)e^+e^- b\bar{b}$ | $m_Z + 2m_b$ | 4 | $9.459 \pm 0.004$ | $15.31 \pm 0.03$ |
| c.4 | $pp \to (\gamma^*/Z \to)e^+e^- t\bar{t}$ | $m_Z + 2m_{top}$ | 5 | $0.0035131 \pm 0.0000004$ | $0.004876 \pm 0.000002$ |
| c.5 | $pp \to \gamma t\bar{t}$ | $2m_{top}$ | 5 | $0.2906 \pm 0.0001$ | $0.4169 \pm 0.0003$ |
| d.1 | $pp \to W^+W^-$ | $2m_W$ | 4 | $29.976 \pm 0.004$ | $43.92 \pm 0.03$ |
| d.2 | $pp \to W^+W^-\, j$ | $2m_W$ | 4 | $11.613 \pm 0.002$ | $15.174 \pm 0.008$ |
| d.3 | $pp \to W^+W^+\, jj$ | $2m_W$ | 4 | $0.07048 \pm 0.00004$ | $0.1377 \pm 0.0005$ |
| e.1 | $pp \to HW^+$ | $m_W + m_H$ | 5 | $0.3428 \pm 0.0003$ | $0.4455 \pm 0.0003$ |
| e.2 | $pp \to HW^+\, j$ | $m_W + m_H$ | 5 | $0.1223 \pm 0.0001$ | $0.1501 \pm 0.0002$ |
| e.3 | $pp \to HZ$ | $m_Z + m_H$ | 5 | $0.2781 \pm 0.0001$ | $0.3659 \pm 0.0002$ |
| e.4 | $pp \to HZ\, j$ | $m_Z + m_H$ | 5 | $0.0988 \pm 0.0001$ | $0.1237 \pm 0.0001$ |
| e.5 | $pp \to Ht\bar{t}$ | $m_{top} + m_H$ | 5 | $0.08896 \pm 0.00001$ | $0.09869 \pm 0.00003$ |
| e.6 | $pp \to Hb\bar{b}$ | $m_b + m_H$ | 4 | $0.16510 \pm 0.00009$ | $0.2099 \pm 0.0006$ |
| e.7 | $pp \to Hjj$ | $m_H$ | 5 | $1.104 \pm 0.002$ | $1.036 \pm 0.002$ |

# Merging NLO and PS

Combine best features

Get correct rates (NLO) and hadron-level description of events (PS)

Difficult because need to avoid double counting

Two working frameworks

- MC@NLO

  Frixione & Webber '02 and later refs.

- POWHEG

  Nason '04 and later refs.

Processes implemented:

- W/Z boson production
- WW, WZ, ZZ production
- inclusive Higgs production
- heavy quark production
- single-top
- dijets
- $W^+W^+$ + dijets ...
- ...

[ ... ]

# POWHEG-BOX

Alioli et al. 1002.2581; http://powhegbox.mib.infn.it

POWHEG-BOX: framework to automatically shower NLO calculations.
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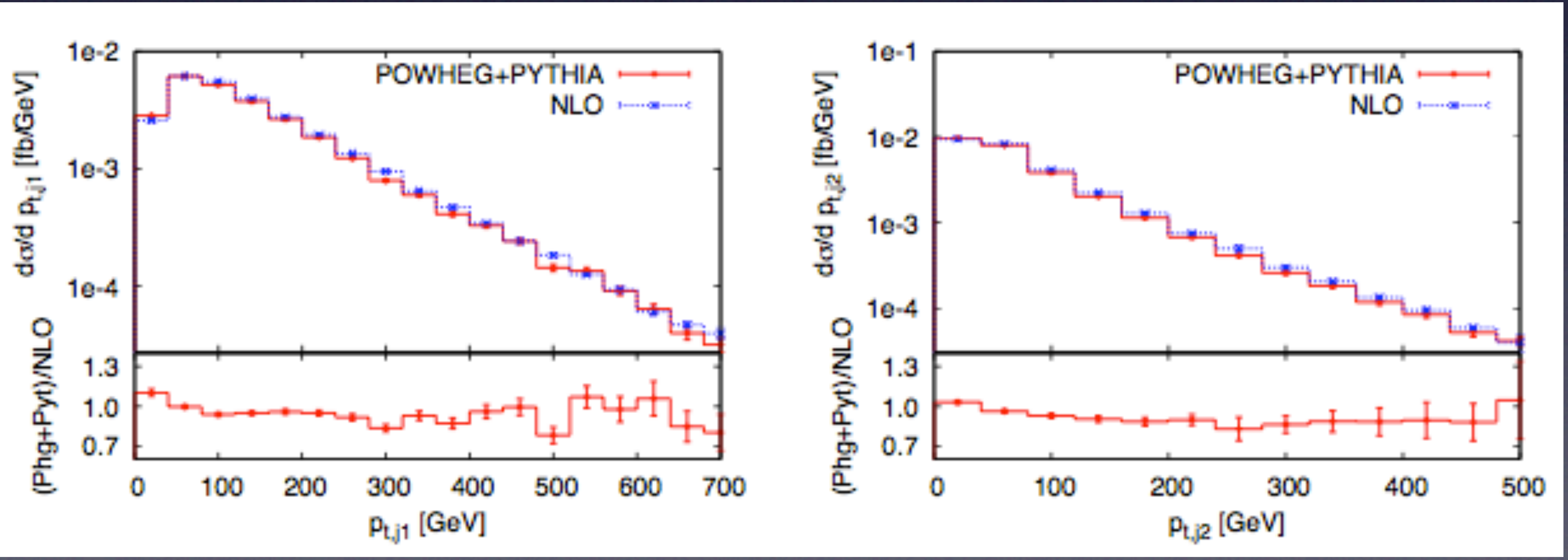
First application to a 2 → 4 process: pp → $W^+W^+$ + 2 jets

Melia, Nason, Rontsch, GZ 1102.4846




✔ nice agreement between NLO & POWHEG+PYTHIA

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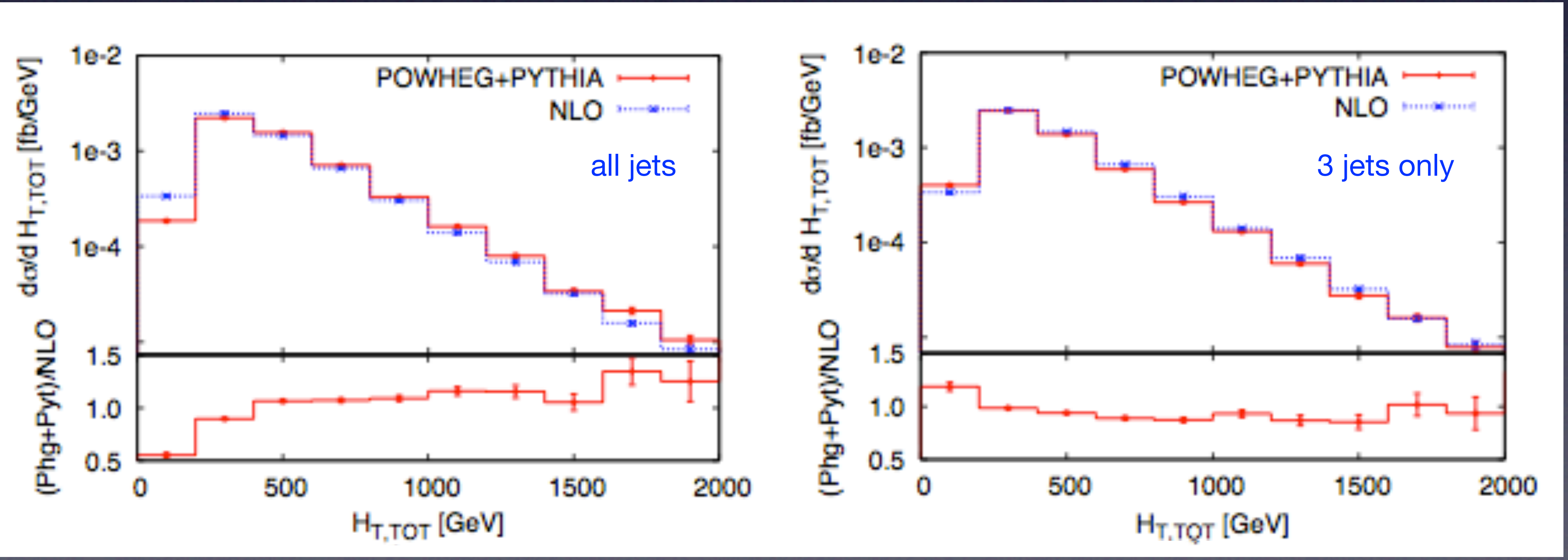


☛ agreement depends on details of observable definition

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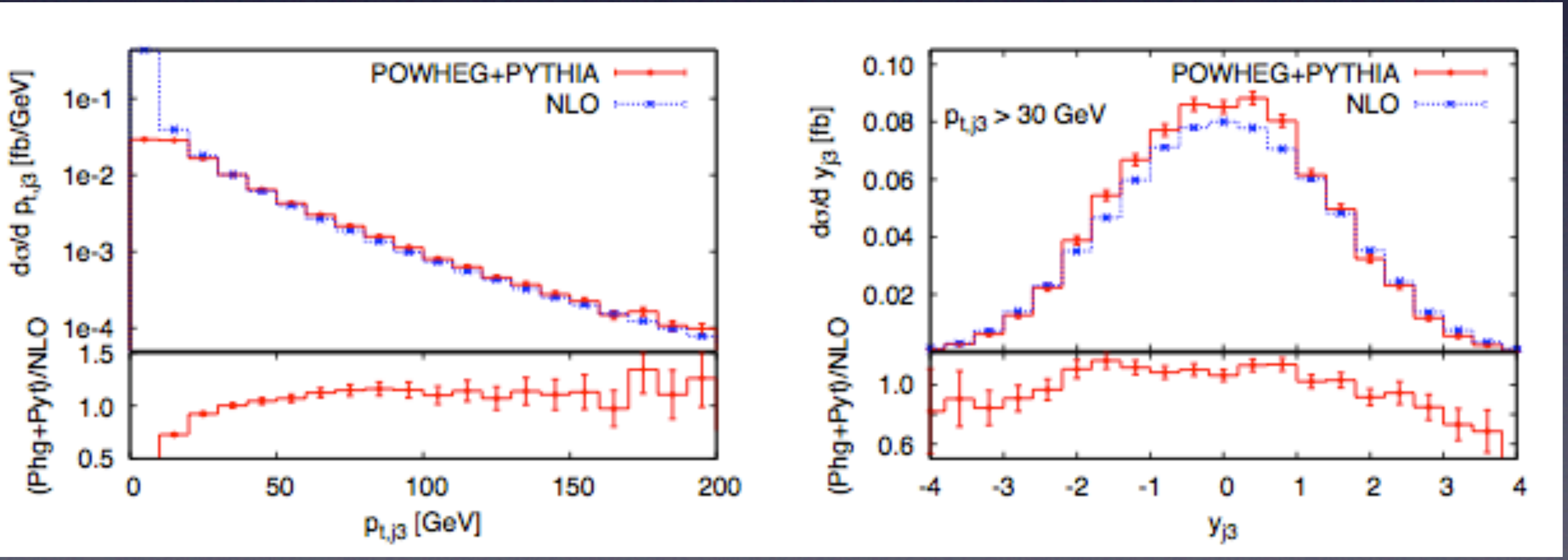



✗ large differences between NLO and POWHEG+PYTHIA

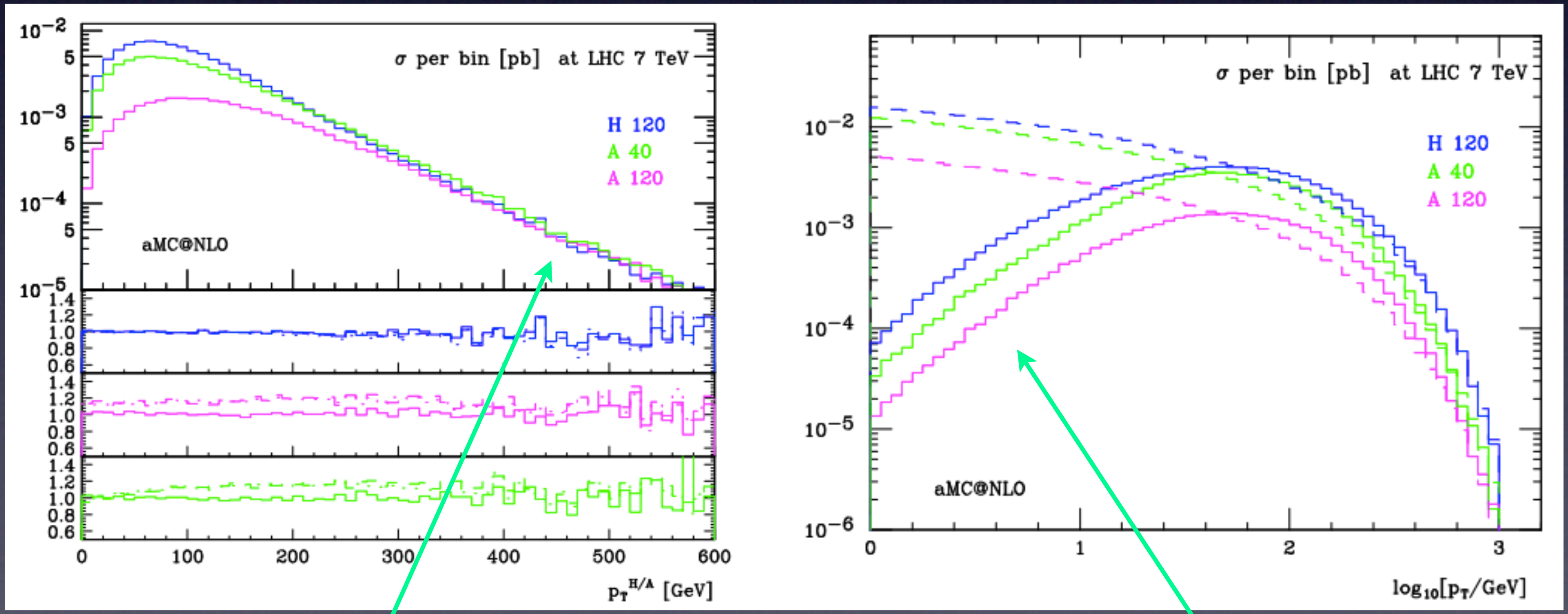
# aMC@NLO

Hirschi et al. 1104.5613

aMC@NLO = Automated complete event generation at NLO

- no public code yet [will be at http://amcatnlo.cern.ch]
- currently only Herwig (Pythia6, Herwig ++ in progress)

First example Htt / Att




Scalar and pseudoscalar very similar at large $p_t$

NLO divergence → Sudakov suppression

# MENLOPS

Hamilton and Nason 1004.1764

Problem: in MC@NLO or POWHEG multi-jet radiation done only in the shower (soft/collinear) approximation

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For example, for W production merge

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2. W+1,2,3 ... jets at LO (exact ME)
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Define jet-multiplicities using $k_t$-algo., then apply the approx. correction:

correct 1-jet fraction using exact ME

correct 2-jet fraction using NLO K-factor

$$d\sigma = d\sigma_{\mathrm{PW}}(0) + \frac{\sigma_{\mathrm{ME}}(1)}{\sigma_{\mathrm{ME}}(\geq 1)} \frac{\sigma_{\mathrm{PW}}(\geq 1)}{\sigma_{\mathrm{PW}}(1)} d\sigma_{\mathrm{PW}}(1j) + \frac{\sigma_{\mathrm{PW}}(\geq 1)}{\sigma_{\mathrm{ME}}(\geq 1)} d\sigma_{\mathrm{ME}}(\geq 2j)$$

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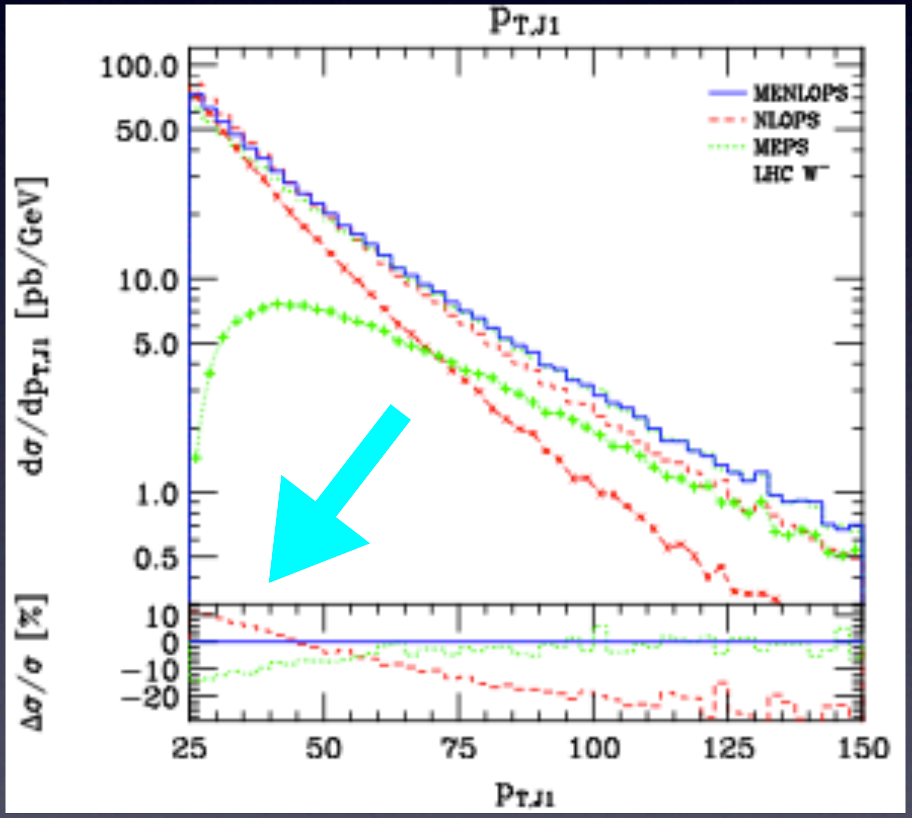
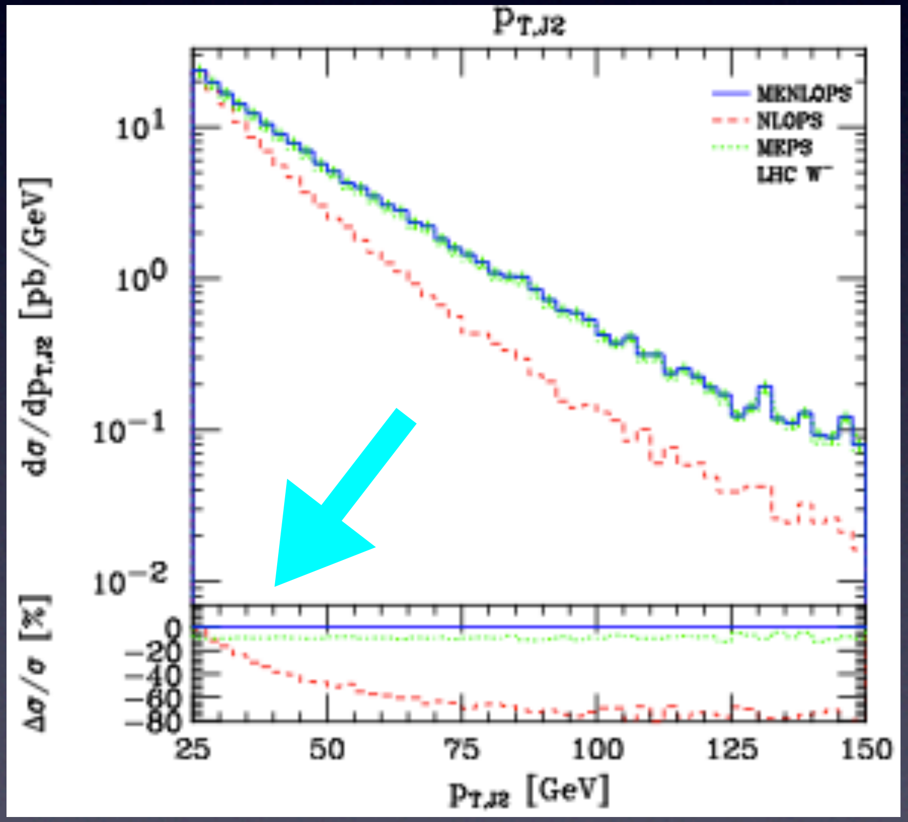
Hamilton and Nason 1004.1764

Jet distributions in W production:




NLO quality accuracy for inclusive quantities but improved sensitivity to hard radiation and multi-parton kinematic features

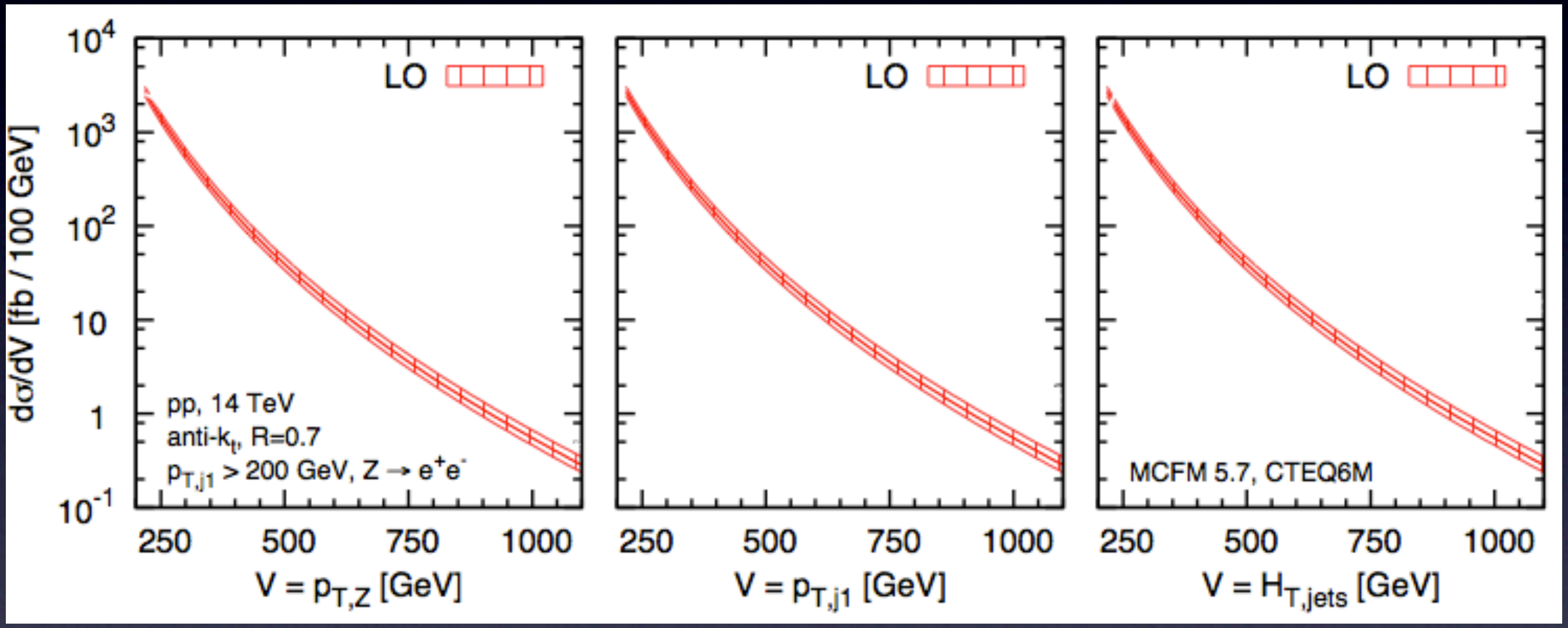
see also Lavesson and Lonnblad 0811.2912; Hoeche et al. 1009.1127

# Giant K-factors

Rubin, Salam, Sapeta 1006.2144

Case study: Z+1jet

Three observables that are equivalent at LO



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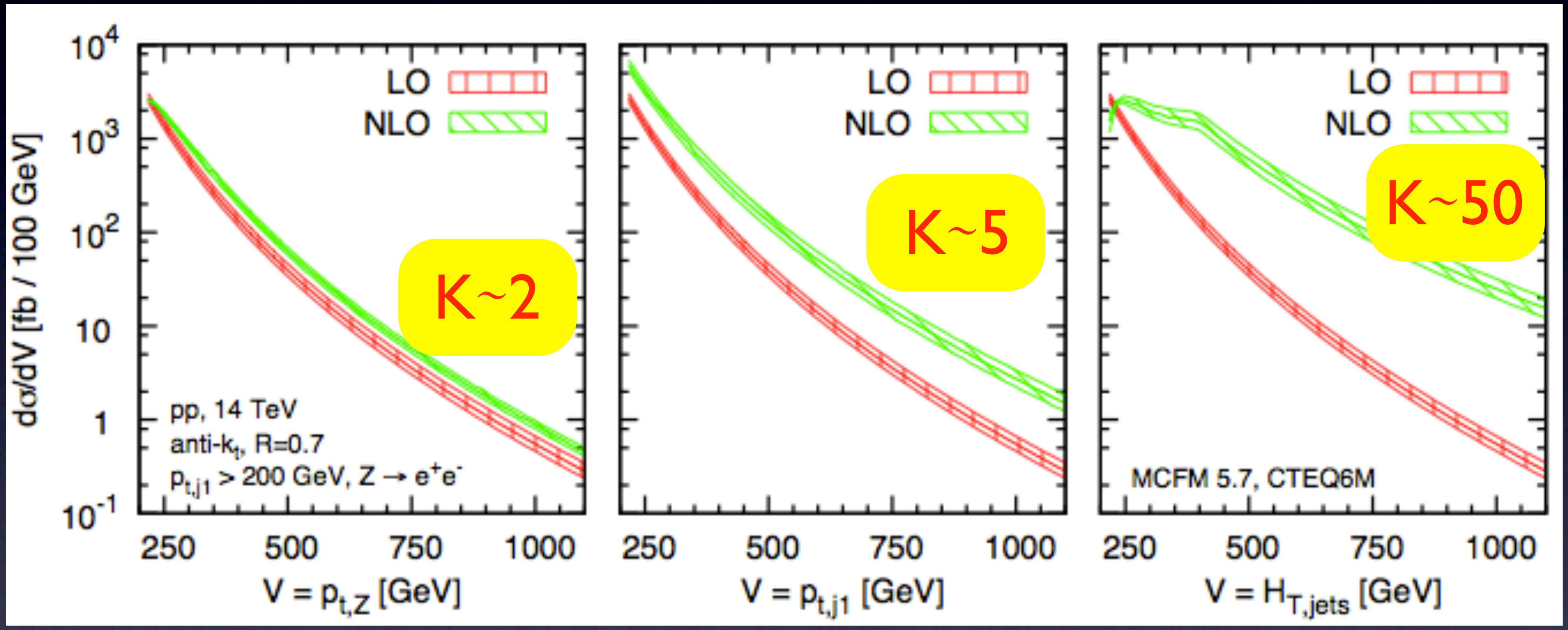

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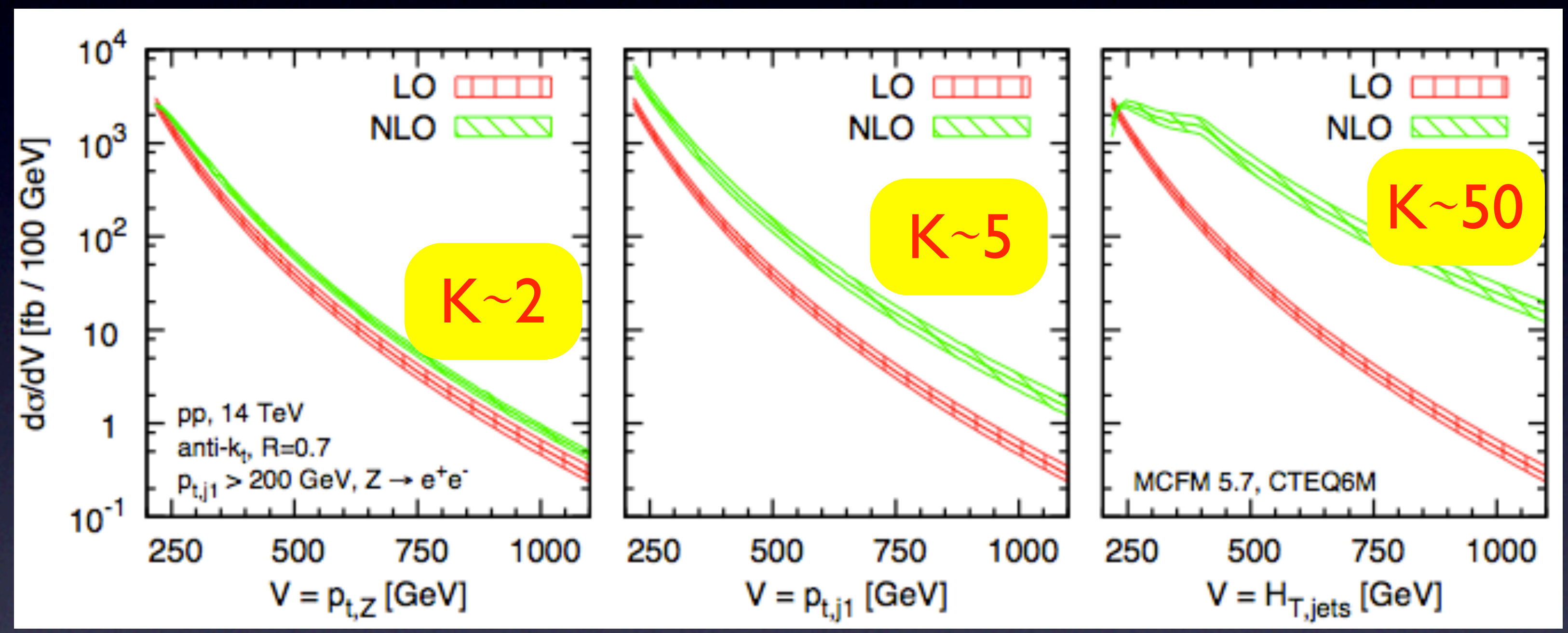


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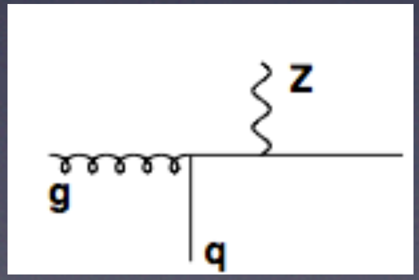
LO: $\alpha_{ew}\,\alpha_s$



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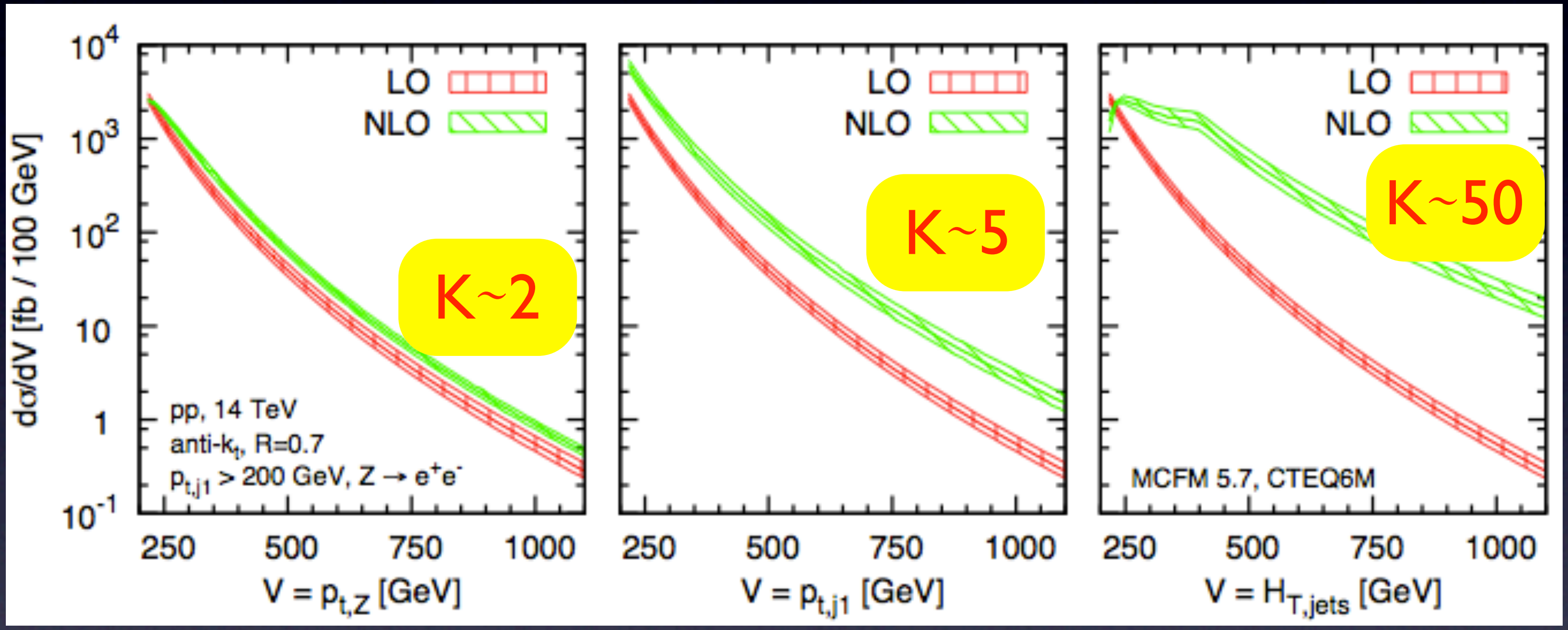


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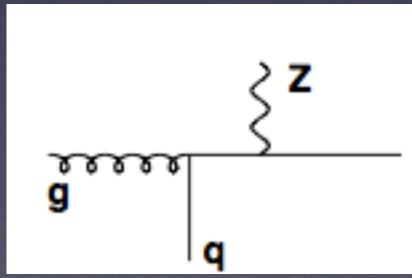
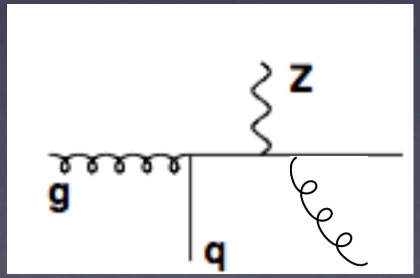



NLO: $\alpha_{ew}\,\alpha_s^2$



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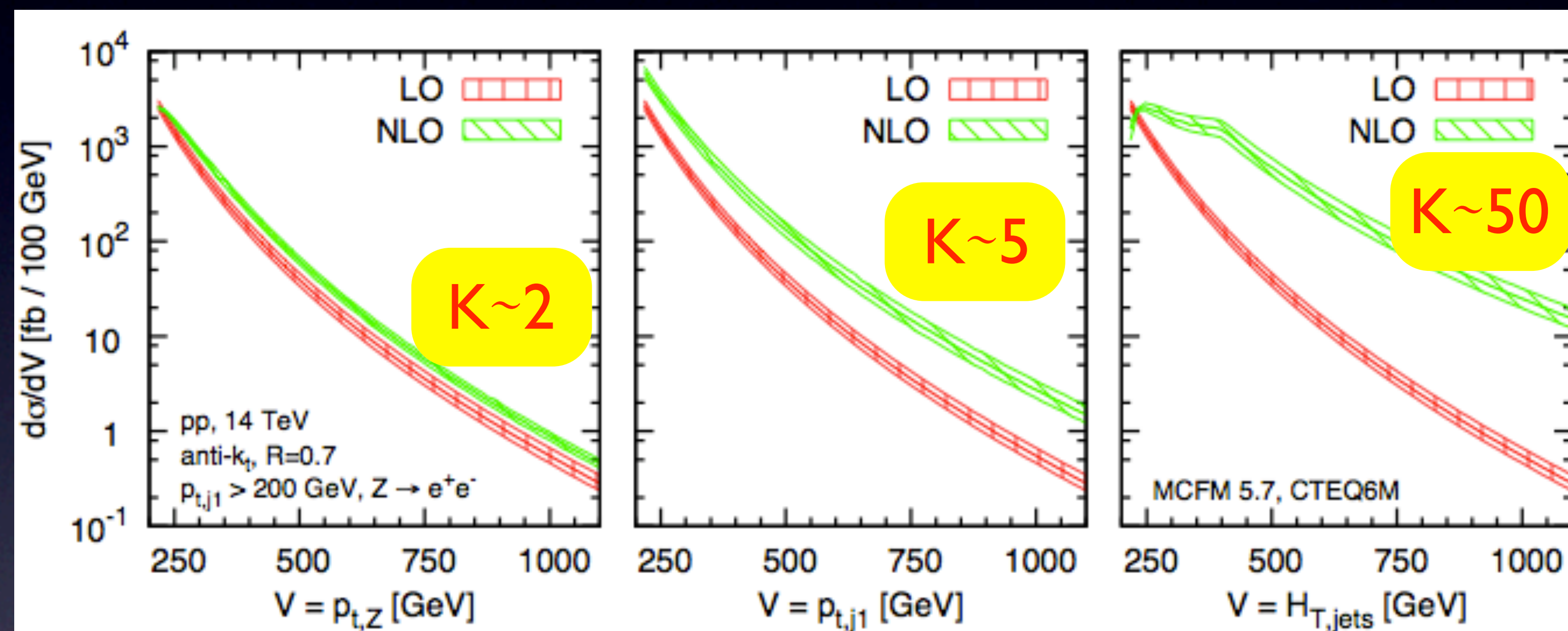


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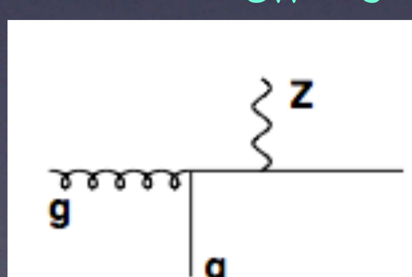


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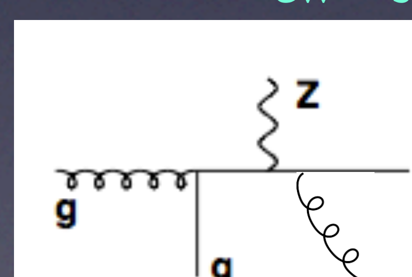
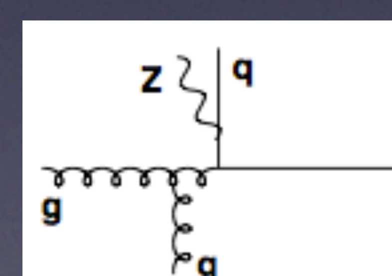
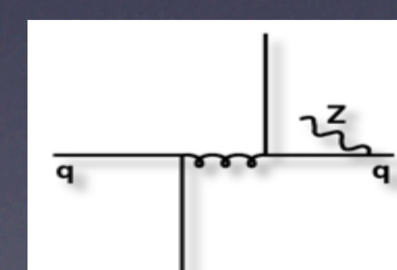



but also

NLO: $\alpha_{ew}\,\alpha_s^2 \ln^2(p_{t,j1}/M_Z)$




Dominant contributions at high $p_t$ (EW logarithms + qq enhancement)

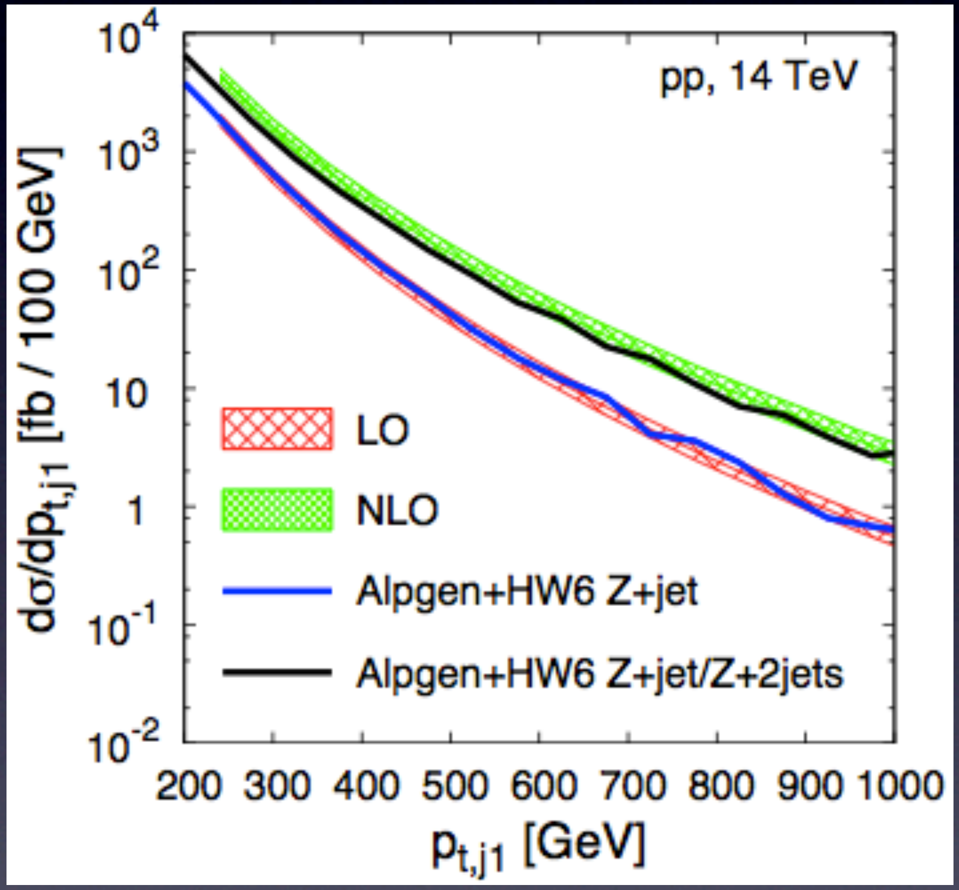
# Giant K-factors

Rubin, Salam, Sapeta 1006.2144

Origin of giant K-factors:

new partonic channels entering at NLO are enhanced wrt LO [i.e. giant K not related to "loop"]

LO matrix element catches the large effect, but has LO quality.
Would like NLO quality on Z+1jet and Z+2jets (extension of MLM/ CKKW procedures)



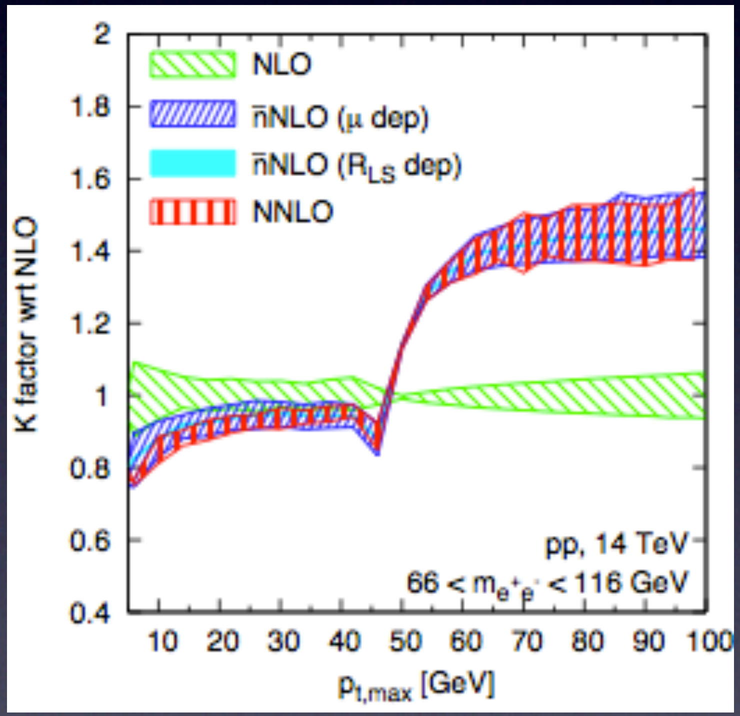

Solution:
LoopSim = approximate method to estimate loops using unitarity to cancel divergences

# Giant K-factors

Rubin, Salam, Sapeta 1006.2144

- use $k_t$ algorithm to determine branching history
- soft particles are "looped" = removed from the event, residual hard event adjusted
- use a unitary operator to cancel divergences
- extension to NNLO simple: apply LoopSim to exact NLO to get approximate two loop

Validation in DY: works well also when K not giant



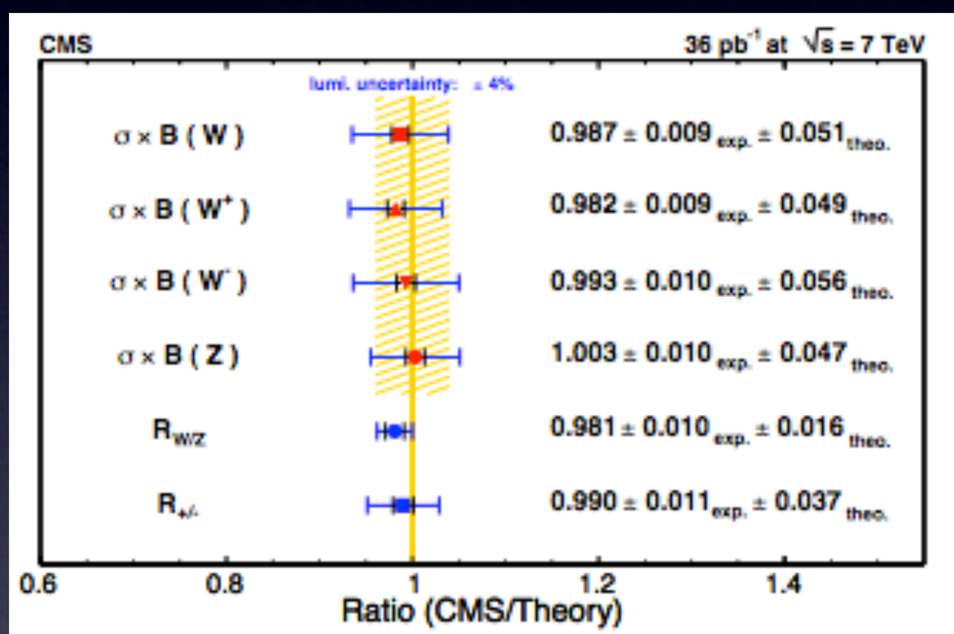

$$\sigma_{\bar{n}\mathrm{NLO}} = \sigma_{\bar{n}\mathrm{NLO}} \left(1 + \mathcal{O}\left(\frac{\alpha_s^2}{K_{\mathrm{NNLO}}}\right)\right)$$

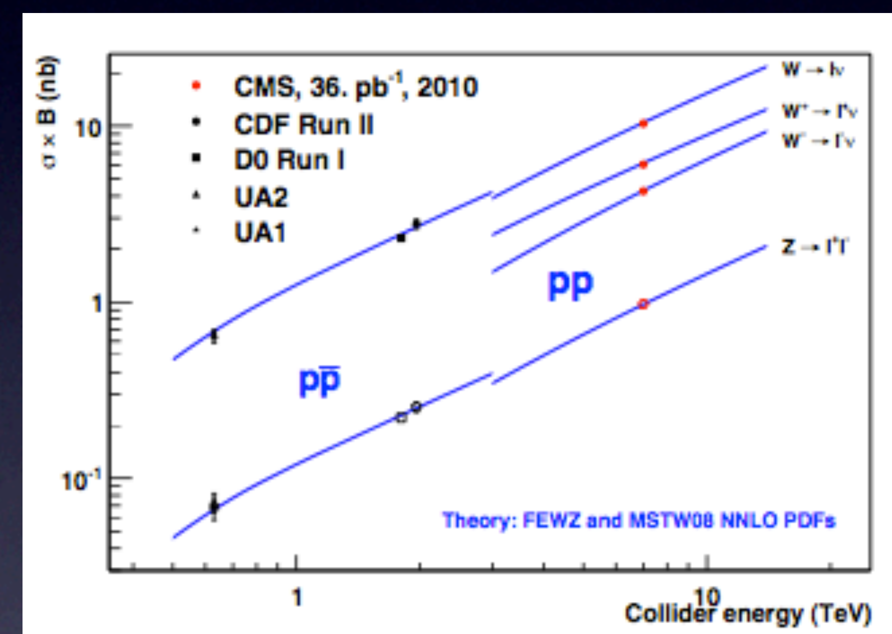
Expect to see other extensions of the MLM/CKKW matching procedures in the near future

# Inclusive W/Z

➠ see talks of S. Forte and F. Petriello

Impressive agreement between NNLO theory and experiment




| Quantity | Ratio (CMS/Theory) | Lumi. uncert. (4%) |
|---|---|---|
| $\sigma \times \mathrm{BF}(W^{\pm})$ | $0.987 \pm 0.009$ (ex) $\pm 0.051$ (th) $[\pm 0.051(\mathrm{tot})]$ | 0.039 |
| $\sigma \times \mathrm{BF}(W^{+})$ | $0.982 \pm 0.009$ (ex) $\pm 0.049$ (th) $[\pm 0.050(\mathrm{tot})]$ | 0.039 |
| $\sigma \times \mathrm{BF}(W^{-})$ | $0.993 \pm 0.010$ (ex) $\pm 0.056$ (th) $[\pm 0.057(\mathrm{tot})]$ | 0.040 |
| $\sigma \times \mathrm{BF}(Z)$ | $1.003 \pm 0.010$ (ex) $\pm 0.047$ (th) $[\pm 0.048(\mathrm{tot})]$ | 0.040 |
| $\sigma \times \mathrm{BF}(W)/\sigma \times \mathrm{BF}(Z)$ | $0.981 \pm 0.010$ (ex) $\pm 0.016$ (th) $[\pm 0.019(\mathrm{tot})]$ | – |
| $\sigma \times \mathrm{BF}(W^{+})/\sigma \times \mathrm{BF}(W^{-})$ | $0.990 \pm 0.011$ (ex) $\pm 0.037$ (th) $[\pm 0.039(\mathrm{tot})]$ | – |

CMS PAS EWK-10-005

# Top

Most interesting SM quark, large mass implies large Yukawa coupling, also prominent decay product in many NP signatures

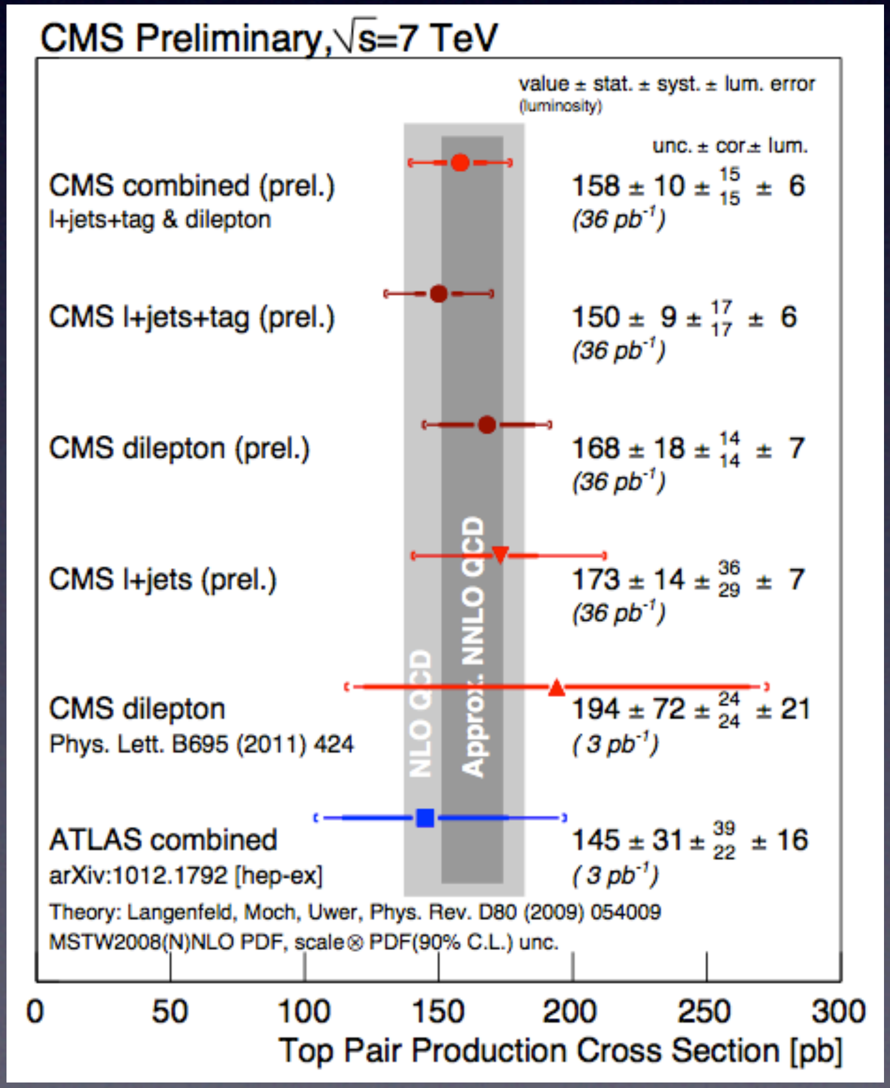
CMS PAS TOP-11-001

Good agreement between LHC data and NLO (approx. NNLO) QCD

Fervid activity towards exact NNLO

[ . . . ]

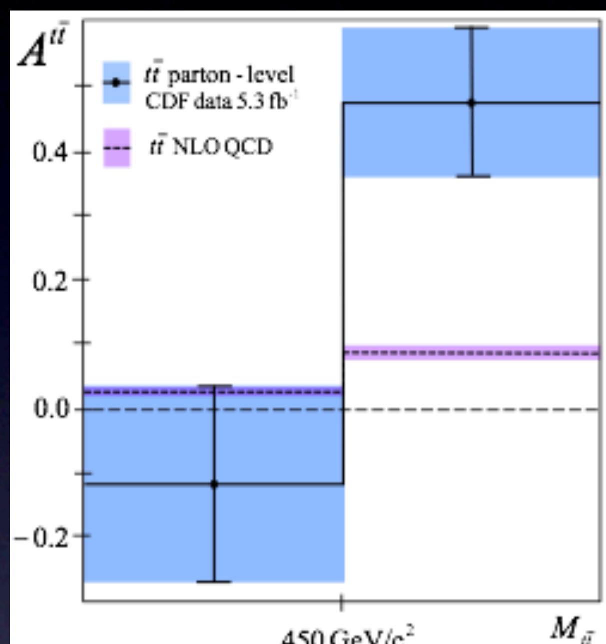
➟ see talk of Eric Laenen



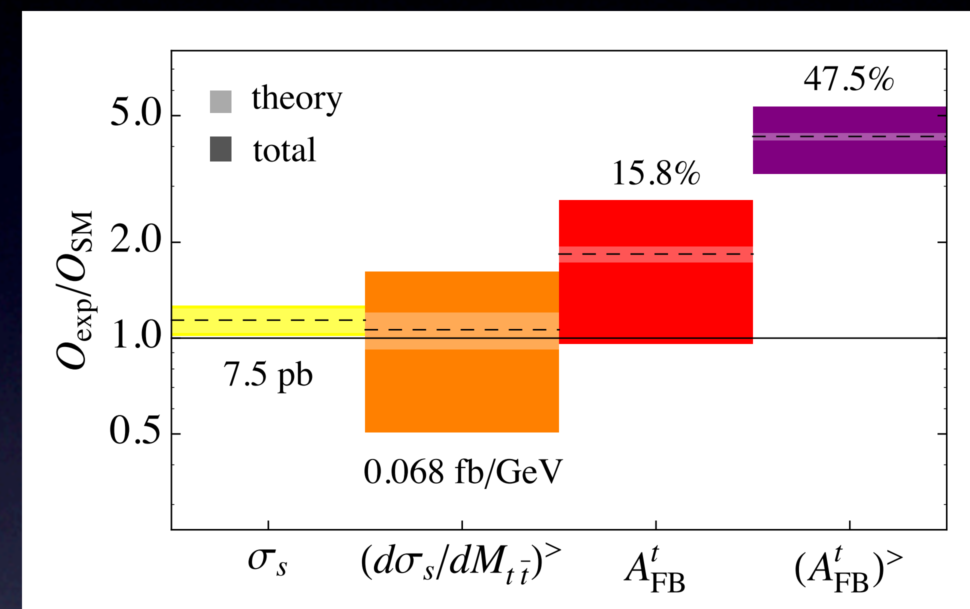

<u>Motivations</u>

- constrain gluon pdf
- top mass from cross-section
- top FB asymmetry

# Top charge asymmetry




Aaltonen et al. 1101.0034




2.7σ / 4.2σ away from the NLO+NNLL theory. Seen both by CDF and D0, effect enhanced at large $M_{tt}$, recently also in dilepton channel

Asymmetry is zero at LO. But theoretical argument suggest that NLO is robust under higher order corrections (unlike asymmetry in tt+1jet)

Melnikov and Schulze 1004.3284

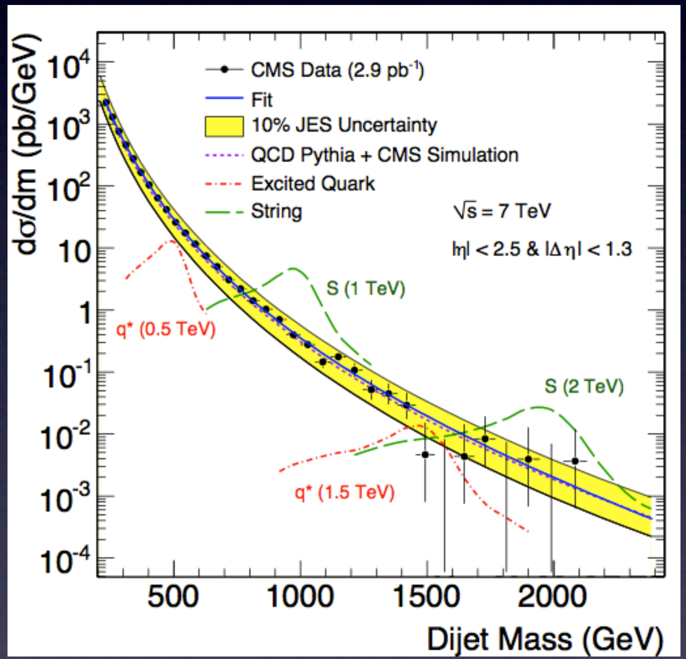
Various new models try to explain data, but difficult to preserve good agreement with symmetric cross-section

# Jet algorithms

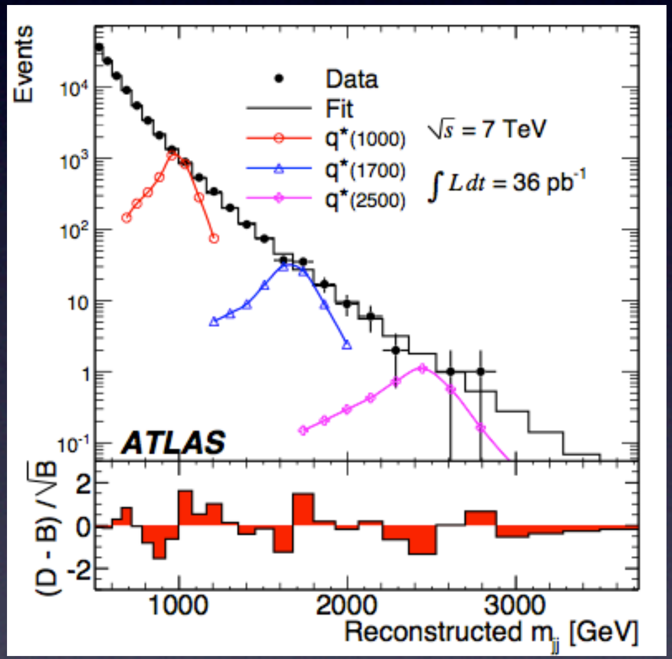
ATLAS and CMS adopted as default jet-algorithm: anti-$k_t$

$$d_{ij} = \frac{1}{\max(k_{ti}^2, k_{tj}^2)} \frac{\Delta R_{ij}}{R}$$

Cacciari, Salam, Soyez '08




CMS PRL 105 (2010)




ATLAS New J. Phys 13 (2011)

So far, at the LHC jets could probe the highest energy scales

~ 2 TeV

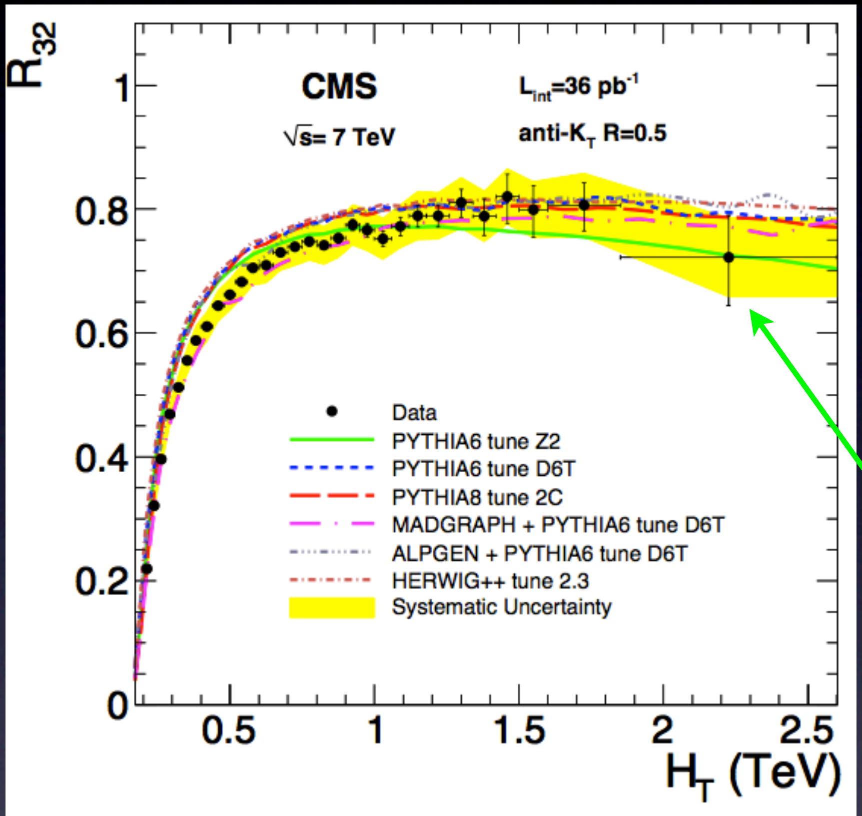
[Tevatron ~ 1 TeV]

Also used: Cambridge-Aachen (CA), $k_t$ algorithm and SISCone

Catani et al. '92-'93; Ellis and Soper '93; Dokshitzer et al. '97; Salam and Soyez '08

All these algorithms are infrared-safe!

# 3 jets / 2 jets ratio




CMS col. 1106.0647

Highest range in $H_T$ ever explored

- agreement with theory (within 20%), but comparison carried out to LO only [large theoretical uncertainties]
- both 2 and 3 jets known to NLO in QCD

Nagy hep-ph/0307268; http://www.desy.de/~znagy/Site/NLOJet++.html

- di-jet production in POWHEG [NLO+Parton Shower]

Alioli et al. 1012.3380; http://powhegbox.mib.infn.it

# Inside jets

➠ see talk of B. Demirkoz for ongoing studies in ATLAS

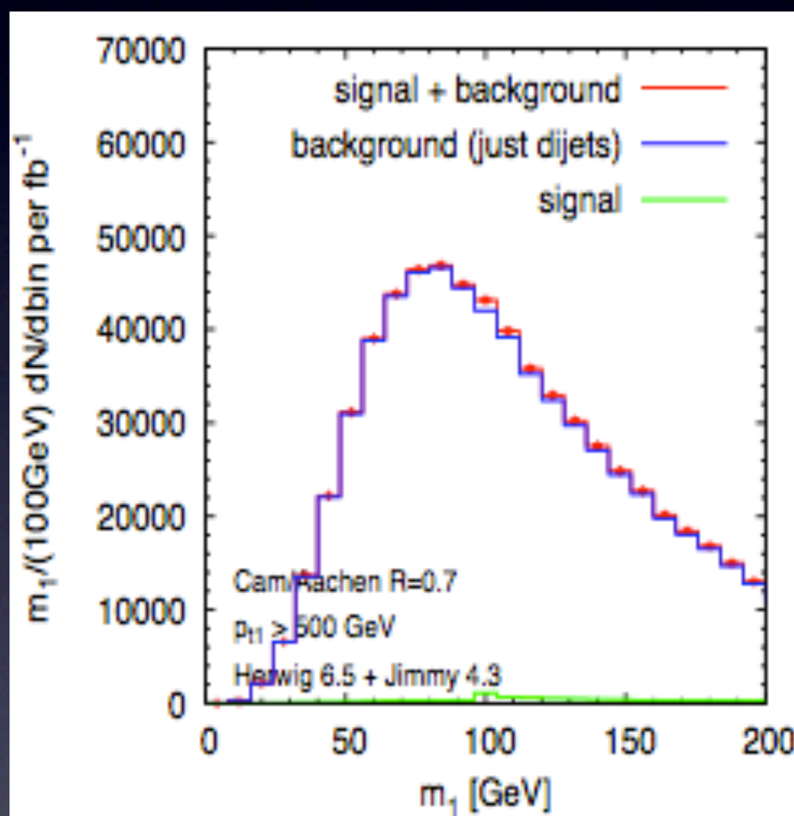
Today, we have a yet more sophisticated description of jets

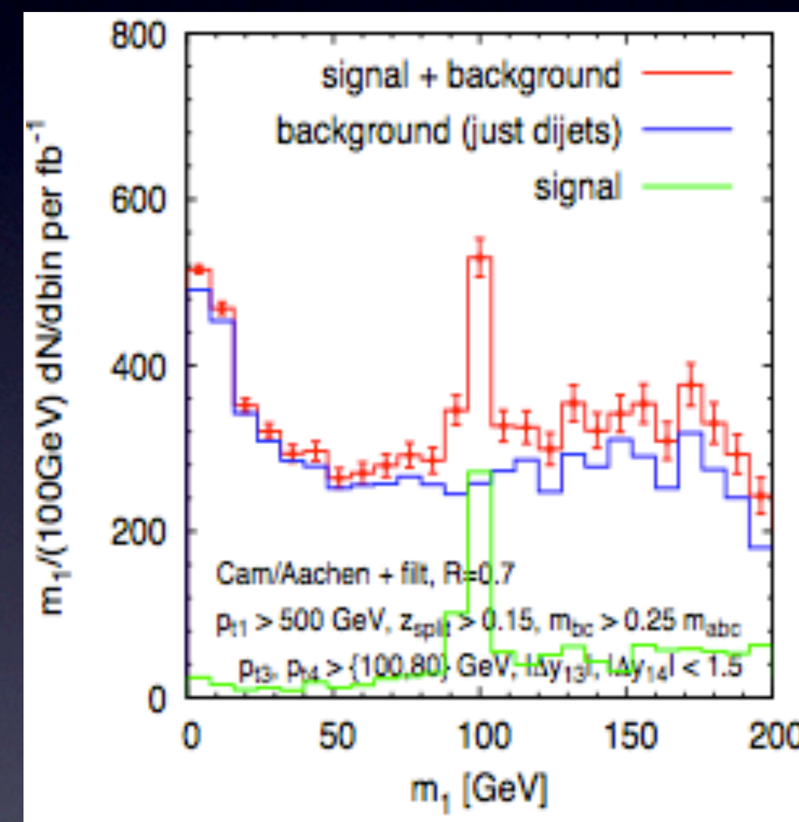
- boosted objects ➛ fat jets
- look inside a fat jet ➛ jet-substructure
- eliminate U.E./P.U. radiation from jet ➛ jet-grooming
  - filtering: e.g. undo last recombinations and keep only few sub-jets
  - pruning: take a jet of interest and recluster it and veto asymmetric wide angle recombinations
  - trimming: regions in a jet with too little energy are discarded

Almeida, Butterworth, Cacciari, Chen, Davison, Ellis, Falkowski, Han, Kribs, Katz, Krohn, Lee, Martin, Nojiri, Perez, Plehn, Raklev, Rehermann, Roy, Rojo, Rubin, Salam, Shelton, Sreethawong, Son, Soyez, Sung, Thaler, Tweedie, Schwartz, Seymour, Soper, Spannowski, Sterman, Virzi, Wang, Zhu ....

# Jets in SUSY

SUSY with R-parity violating decays $\tilde{\chi}_1^0 \to qqq$ most difficult challenge




Look inside the jets with method of Butterworth et al. 0906.0728

Sophisticated jet studies a young field. No precise rules for systematically making discoveries easier. Potential demonstrated, more “work in progress”

➠ http://boost2011.org

# Conclusions

QCD is a very dynamic field. Amazing progress in recent years, I hope I managed to convey a flavor of it

- amazing technical achievements (higher multiplicities and/or loops)
- clever merging to catch best features of different calculations
- ingenuity in refining observables
- sophisticated techniques for looking inside jets
- also spectacular formal developments [IR/UV structures, $\mathcal{N}$=4 or $\mathcal{N}$=8 SYM, twistors, Wilson loops ⇔ amplitudes, symbols ...]
- ...

*"Science progresses best when observations force us to alter our preconceptions"*

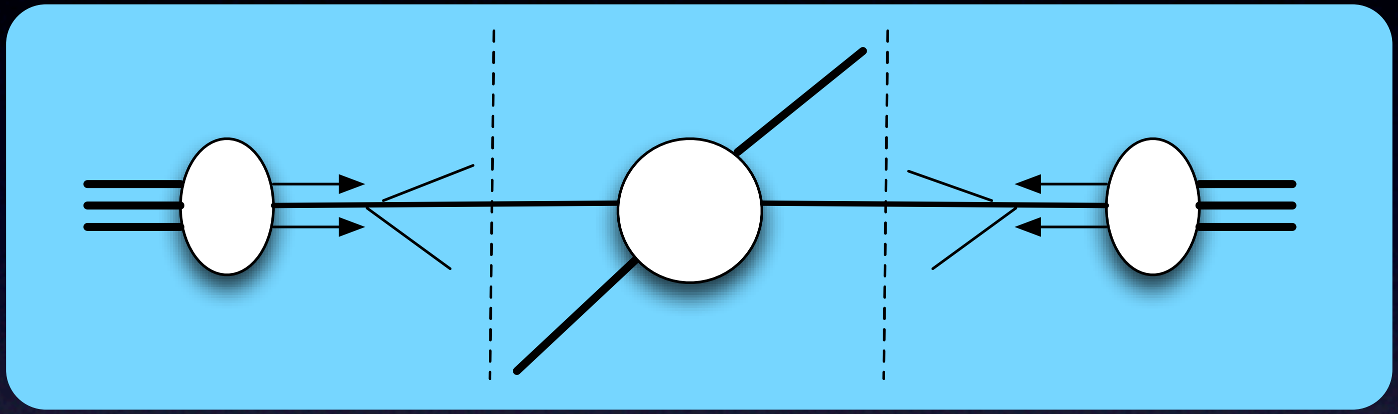
V. Rubin

SM established at the LHC, now waiting eagerly for signs of new physics. We have the right tools to make the most out of observations at the LHC, *but is it really up to you to choose the right observables & tools for your analysis*

# *Extra Slides*

# Pdfs: recent progress

➟ see talk of Stefano Forte

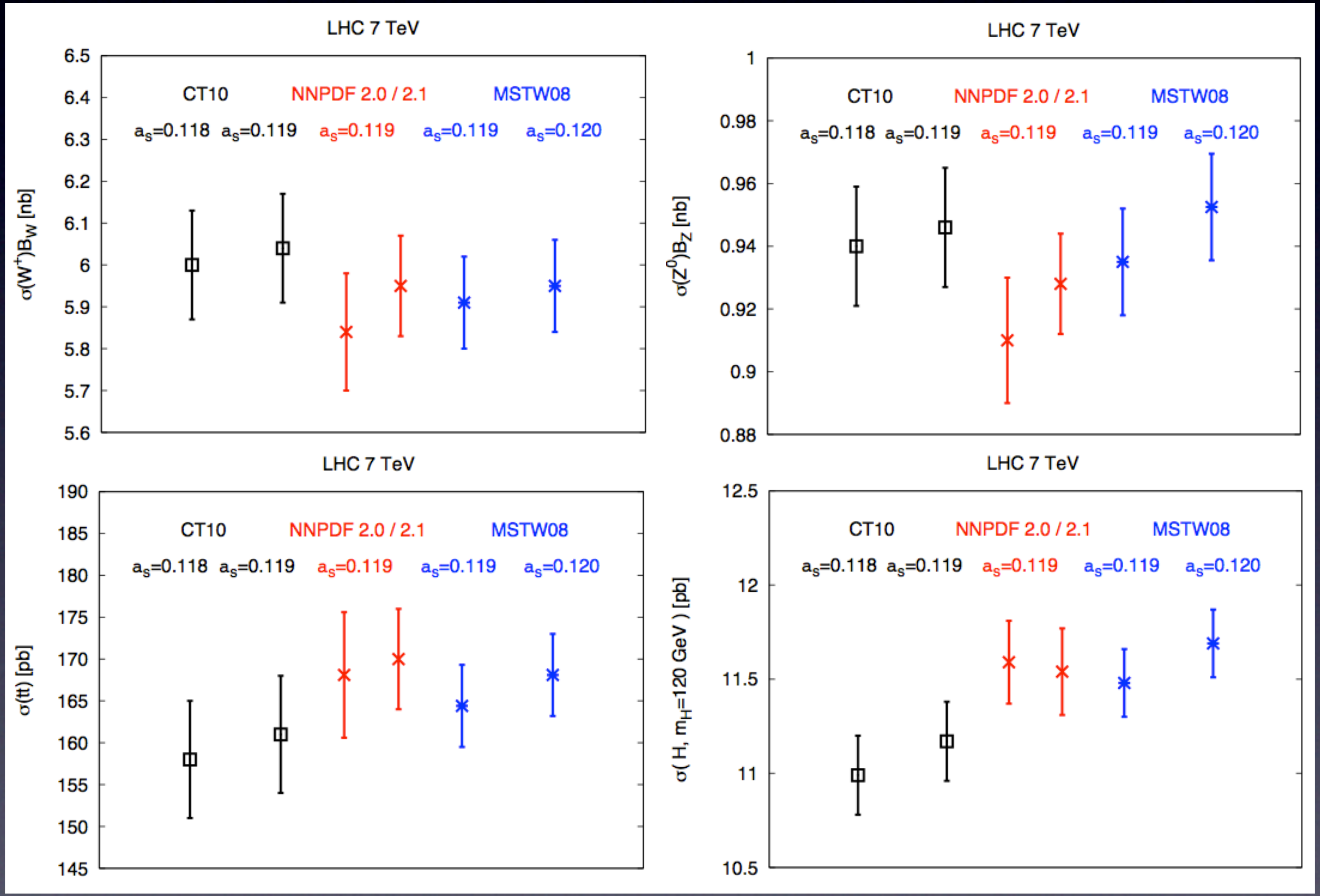


- NNLO evolution, thanks to seminal work of Moch, Vermaseren, Vogt (2004) on NNLO splitting functions
- improved treatment of heavy quarks
  [but various schemes, ad hoc procedures]
- more systematic treatment of uncertainties, including parametrization, heavy flavor scheme, higher orders
  [but still inconsistencies between different groups/data sets]
- global fits using Neural Network pdfs

# Benchmark processes

➠ see talk of Stefano Forte

Uncertainty from pdfs and $\alpha_s$ on benchmark processes

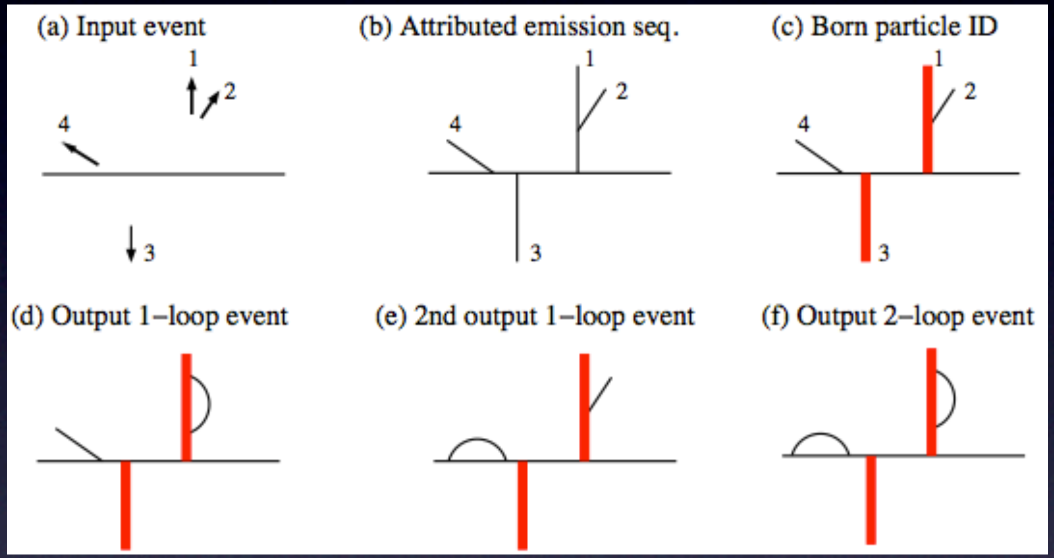



NN col.‘11

# Giant K-factors

Rubin, Salam, Sapeta '10

- use soft algorithm to determine branching history
- soft particles are "looped" = removed from the event, residual hard event adjusted
- use a unitary operator to cancel divergences
- extension to NNLO simple: apply LoopSim to exact NLO to get approximate two loop




$$U_{\forall}(\text{event}) = \sum_l U_l(\text{event})$$

$U_l(\text{event}) =$ simulate l-loops in the event

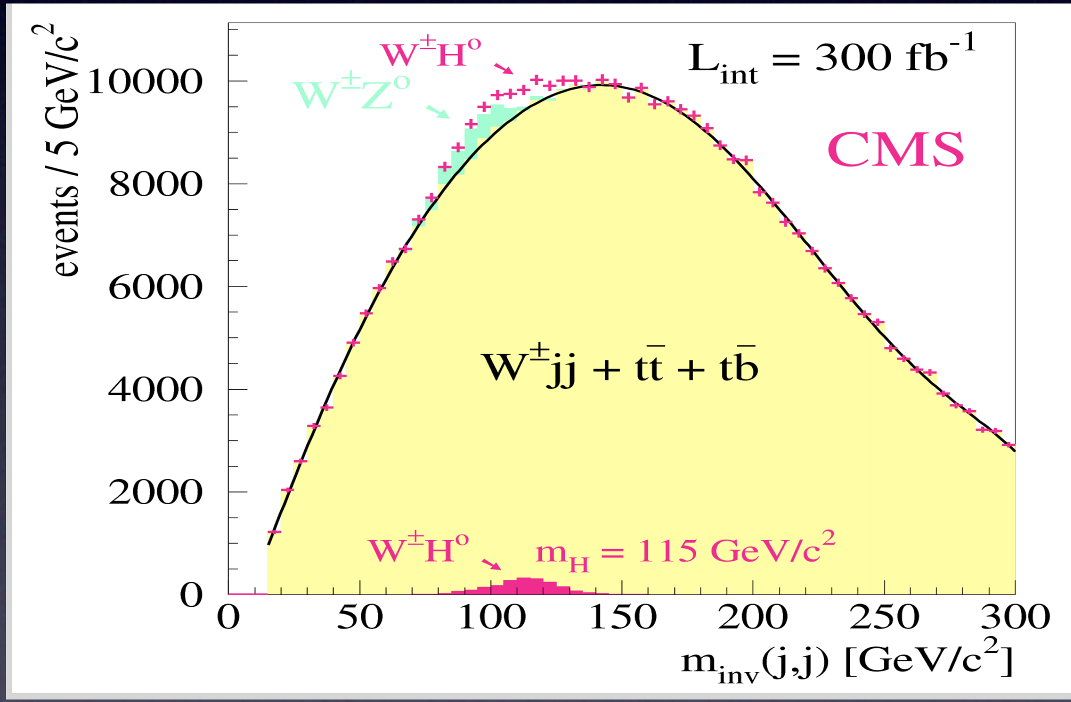
Examples:

$$Z + j@\bar{\text{n}}\text{LO} \equiv Z + j@\text{LO} + U_{\forall}(Z + 2j@\text{LO})$$

$$Z + j@\bar{\text{n}}\text{NLO} \equiv Z + j@\text{NLO} + U_{\forall}(Z + 2j@\text{NLO})$$

# Jets in Z+H (→ bb)

Recall why this search channel is hard:




$$\sigma(\mathrm{pp} \to WH(bb)) \sim \text{few pb}$$

$$\sigma(\mathrm{pp} \to bb) \sim 400\mathrm{pb}$$

$$\sigma(\mathrm{pp} \to Wbb) \sim \text{few pb}$$

$$\sigma(\mathrm{pp} \to tt) \sim 800\mathrm{pb}$$

$$\sigma(\mathrm{pp} \to Wjj) \sim \text{few } 10^4\mathrm{pb}$$

*"The extraction of a signal from H → bb decays in the WH channel will be very difficult at the LHC even under the most optimistic assumptions [...]"*

*ATLAS TDR '99*

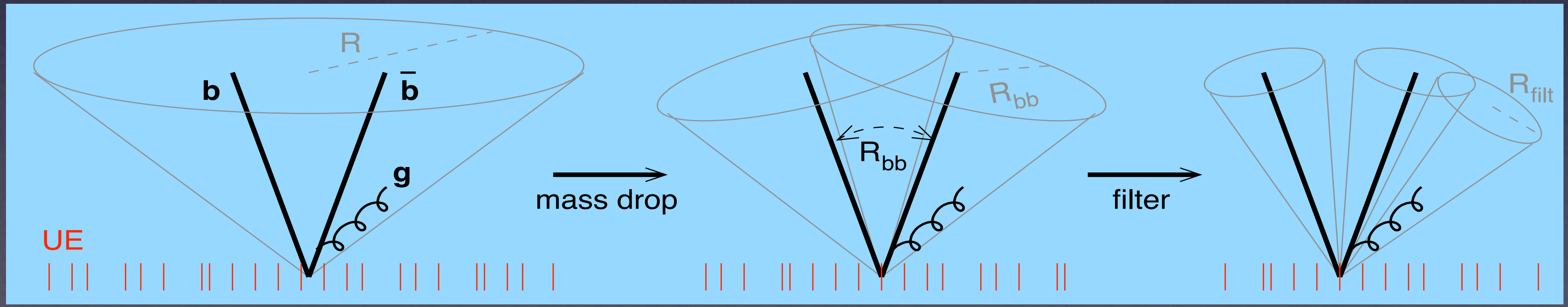
# Jets in Z+H (→ bb)

Butterworth et al. '08

Central idea: require boosted (high-$p_T$) W and Higgs bosons in the event

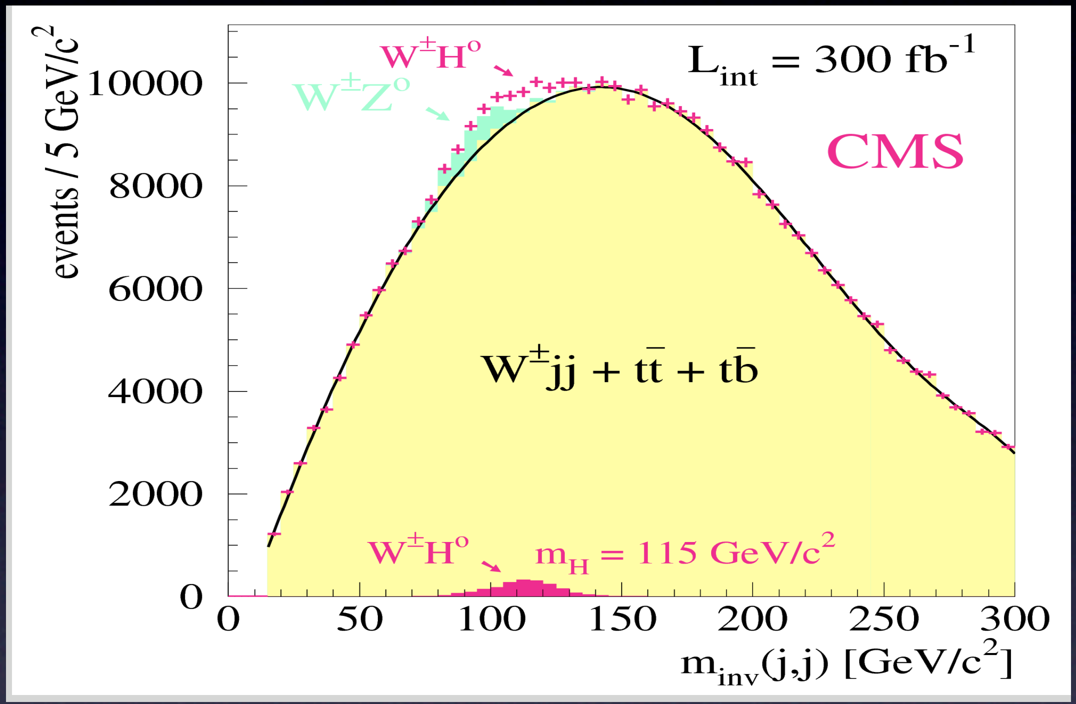
- leads to back-to-back events with two b-quarks in the same jet
- high $p_T$ reduces the signal but reduces the background much more
- high $p_T$ improves acceptance and kinematic resolution

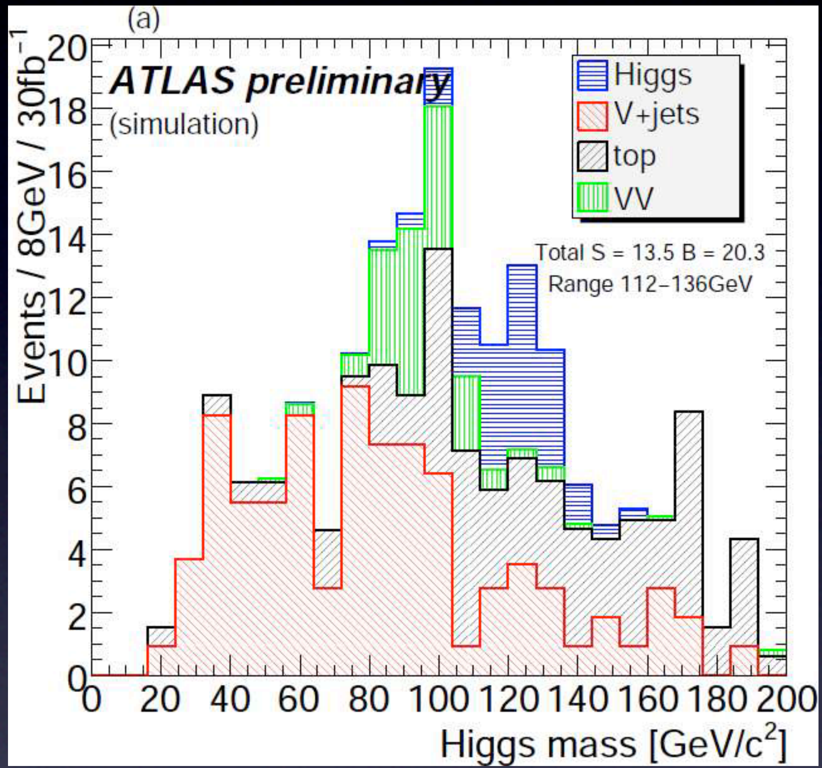
Then use a jet-algorithm geared to exploit the specific pattern of
H → bb (symm.) vs g → gg, q → gg (hard → hard+soft)




1. cluster event with CA algo (large R)
2. undo last step: mass drop + symm. + b tags
3. filter UE: take only the 3 hardest subjets

# Jets in Z+H (→ bb)




Look into the jets with method
of Butterworth et al. ’08

Similar methods to “look into jets” used to recover difficult ttH channel

Plehn et al. ’09

Sophisticated jet studies a young field. No precise rules for systematically making discoveries easier. Potential demonstrated, more “work in progress”