QCD: from benchmark processes to discovery channels

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Benchmark vs. discovery

The term benchmarking was first used by cobblers to measure people's feet for shoes. They would place someone's foot on a "bench" and mark it out to make the pattern for the shoes. Benchmarking is used to measure performance using a specific indicator (...) resulting in a metric of performance that is then compared to others. ...

[Wikipedia]

For us, benchmark processes are usually "simple" Standard Model processes that we use to

- make sure that detectors are well understood
- make sure that theory errors of predictions are under control
- test, re-test, and test again the SM, in particular measure all possible properties of the states involved
- a benchmark process becomes a potential discovery channel as soon as any significant discrepancy in an observable is found (e.g. Wjj, tt, ...)

Discovery channels are those which are inherently sensitive to yet unmeasured physics (because of cuts or process dependent features)

Drell-Yan

The simplest benchmark is Drell-Yan: Z/W production (W → lν , Z → l^+l^-)

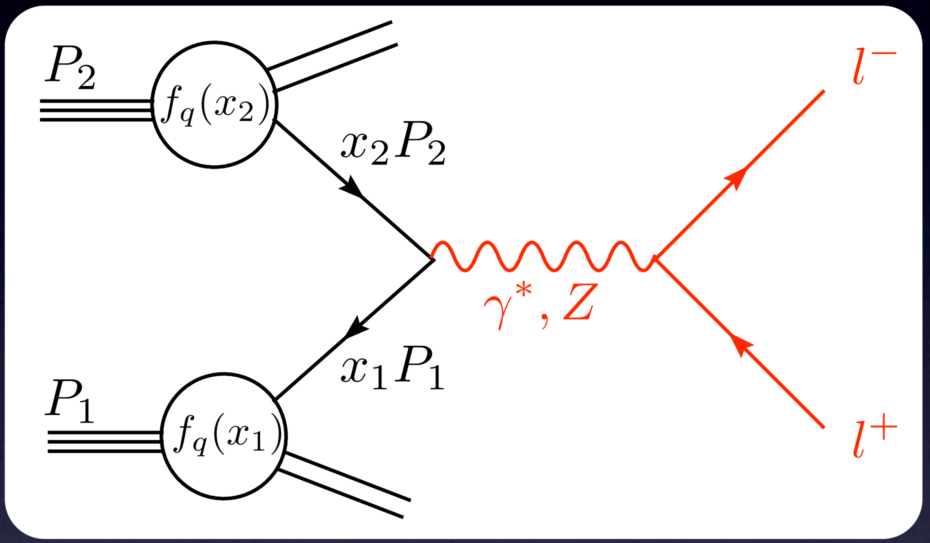
Golden processes because

✓ dominated by quarks in the initial state

✓ no gluons or quarks in the final state at LO

✓ leptons give clear signature

⇒ as clean as it gets at a hadron collider



Inclusive cross-section computed as

hadronic cross-section

parton distribution functions (PDFs)

partonic cross-section

hadronization corrections

$$\sigma = \int dx_1 dx_2 f(x_1, \mu_F) f(x_2, \mu_F) \hat{\sigma}(x_1, x_2; \{p\}; \mu_R, \mu_F) + \mathcal{O}\left(\frac{\Lambda_{\mathrm{QCD}}}{Q}\right)^n$$

known to NNLO

known to NNLO

Drell-Yan

Best known process at the LHC

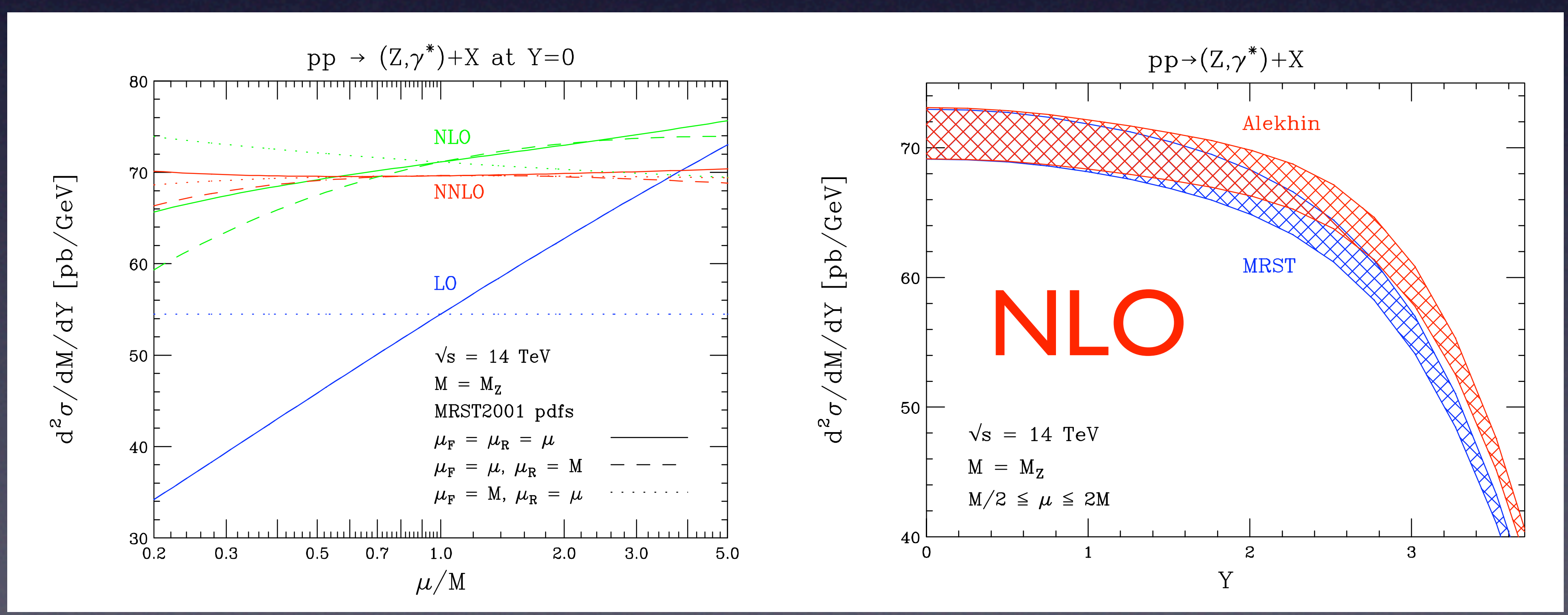
✓ known at NNLO in QCD + NLO EW, differential in lepton momenta including spin-correlations, finite-width effects, γ-Z interference

FEWZ Melnikov, Petriello '06; DYNNLO Catani et al. '09

✓ also NNLL transverse momentum and soft gluon resummation

ResBos Balazs and Yuan '97; Bozzi et al. '11

Scale stability and sensitivity to PDFs



Anastasiou, Dixon, Melnikov, Petriello '03, '05; Melnikov, Petriello '06

☛ *LHC: perturbative accuracy of the order of 1%. This is absolutely unique.*

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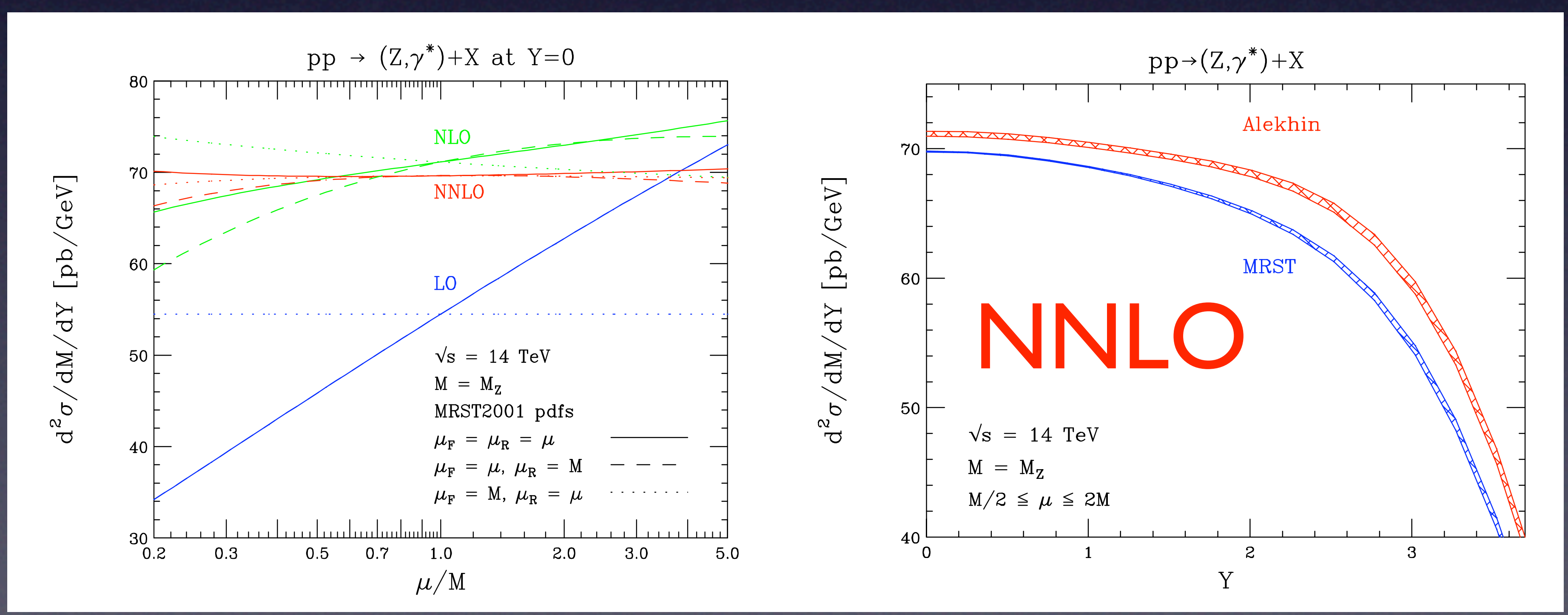

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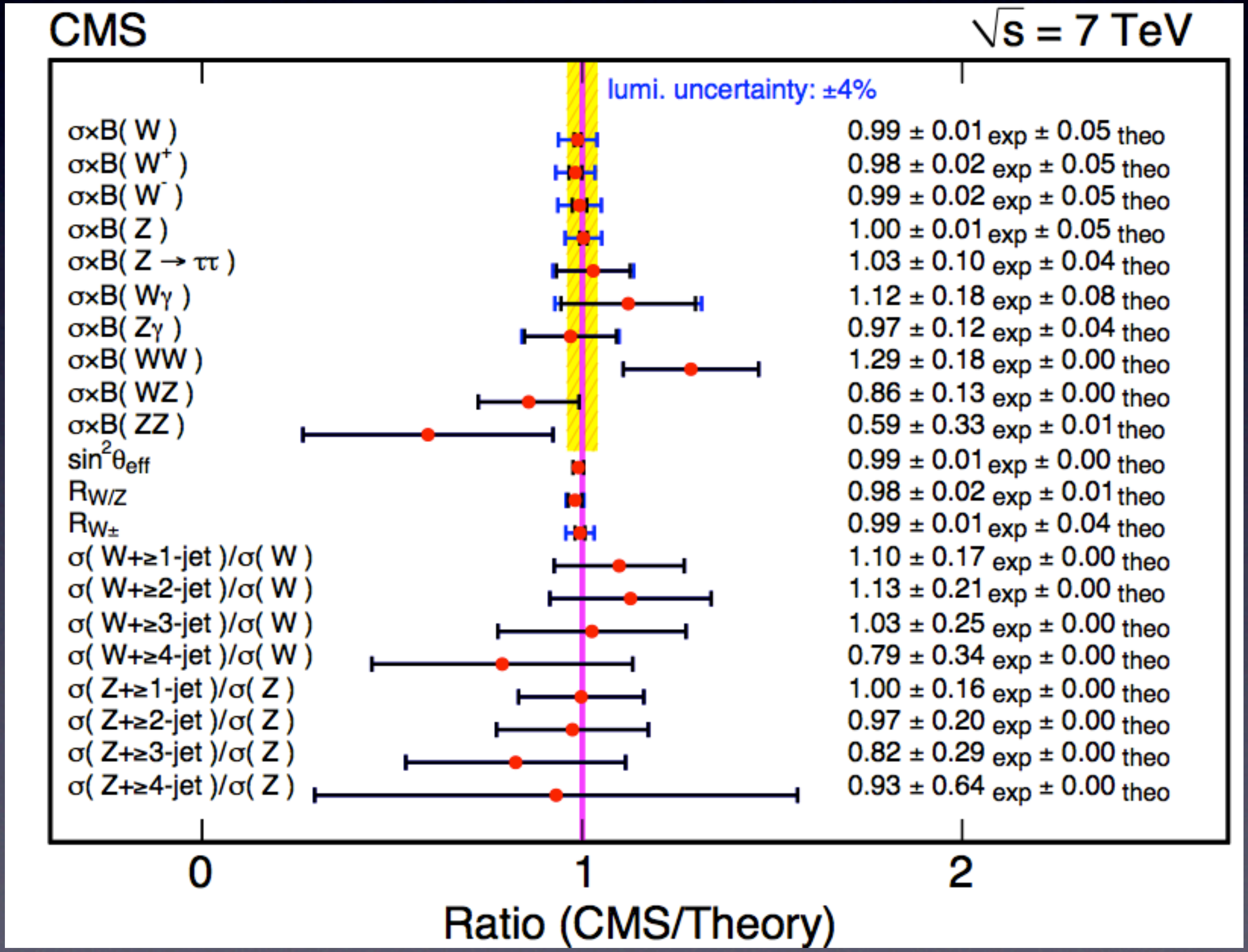
Theory vs. LHC data

Spectacular experimental achievements in very little time!

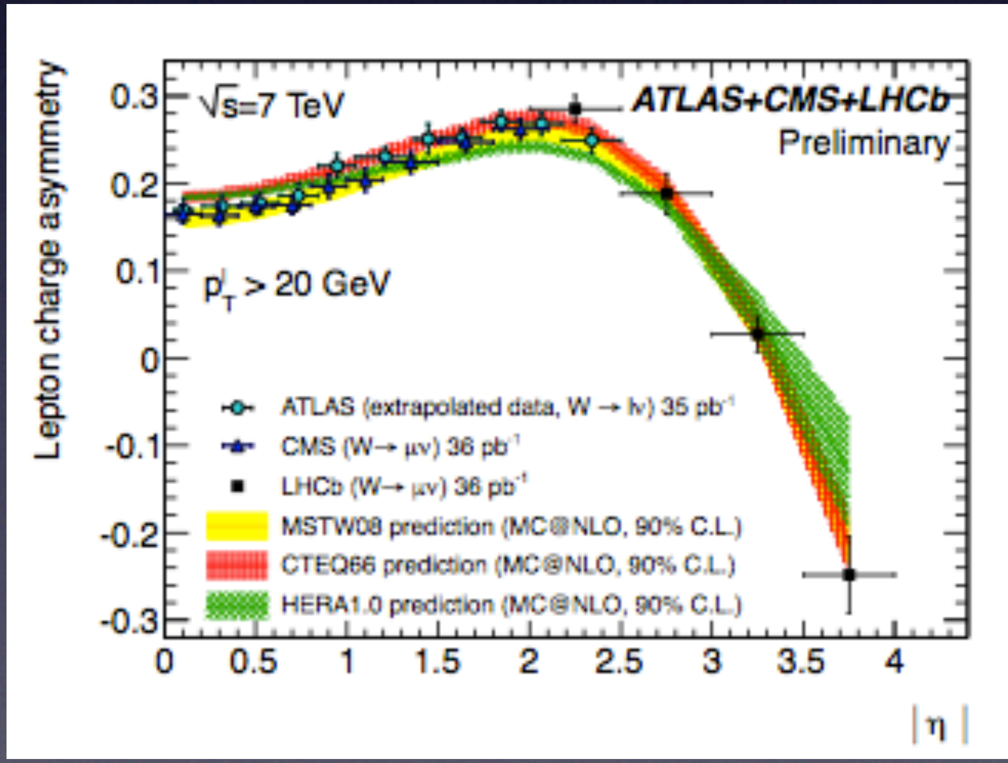


- remarkable agreement with theory
- precise measurement of W/Z properties (couplings of Z to fermions, angular distributions, $\sin^2\theta_W$, ...)
- achieved control and precision already allows improvements on PDFs

Charge asymmetry

Natural extension of the inclusive cross-section is the R_W = W+/W- ratio. Study R_W as a function of kinematics variables, e.g. charge asymmetry as a function of lepton rapidity

$$A(\eta) = \frac{R_W(\eta) - 1}{R_W(\eta) + 1}$$

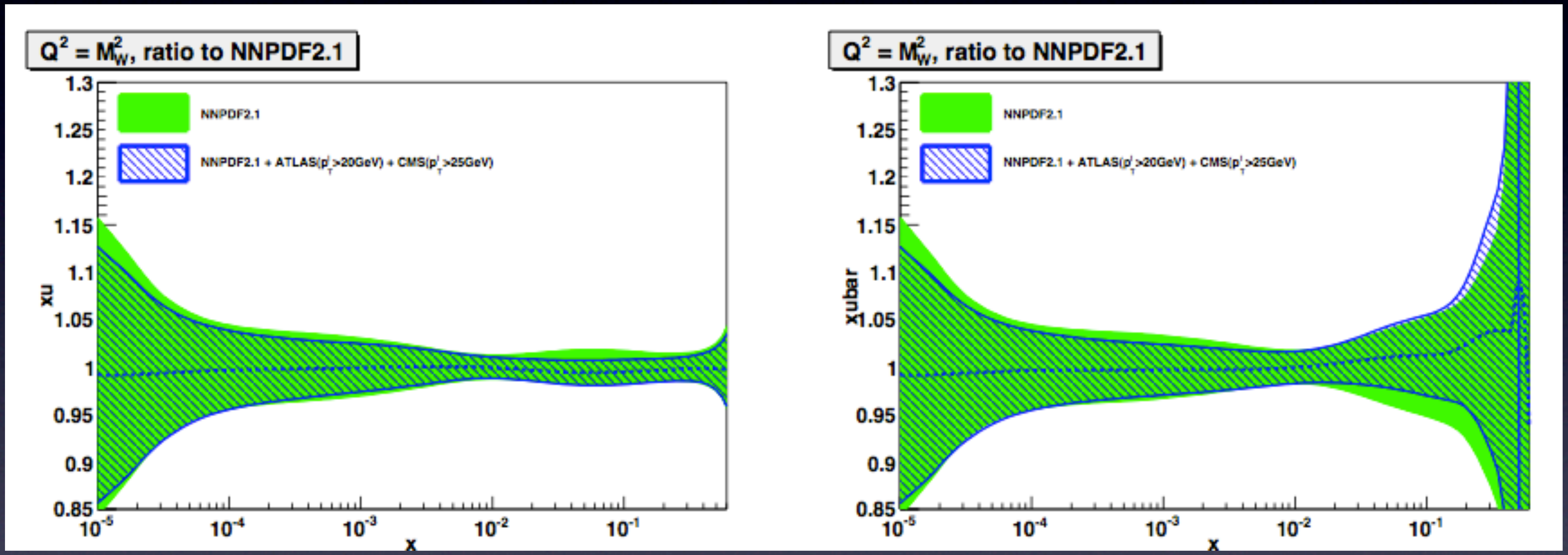


- originates from $W^+(W^-)$ being produced mainly by u (d) quarks that have a different distribution
- measurement very sensitive to PDFs (many uncertainties cancel in ratios)
- large rapidity probe small/large x

➥ good agreement with different PDFs but very sensitive to shape details

Charge asymmetry

First study of effect of ATLAS/CMS lepton charge asymmetry on PDF fits:



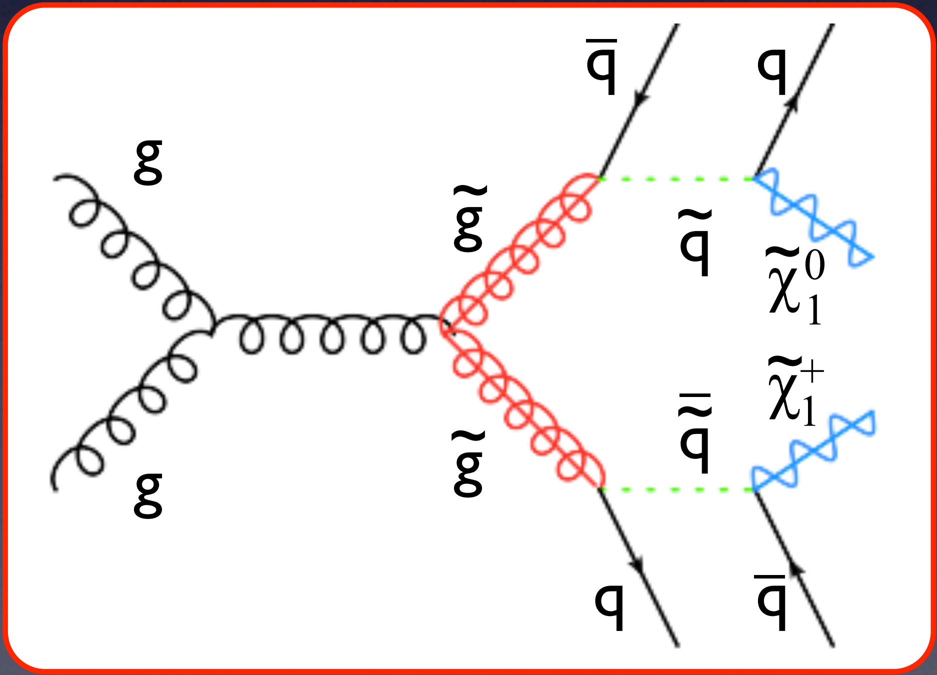
NNPDF 1108.1758

- Reduction of uncertainty of the order of 10-30% in the range $x=10^{-3}-10^{-1}$
- Similar results for d-quark and other sea-quark distributions
- Inclusion of 2011 and LHCb data will reduce the uncertainty further, especially at small and large x

V + jets

Beyond inclusive W/Z production, the production in association with jets is of high interest:

- given the high energy at the LHC, bosons are produced most naturally together with jets
- New Physics signatures typically involve jets, $E_{T,miss}$ and leptons. Thus, W/Z + jets are important backgrounds to New Physics searches



However, precision studies require these processes to be known at least at NLO in QCD (examples follow)

V + jets

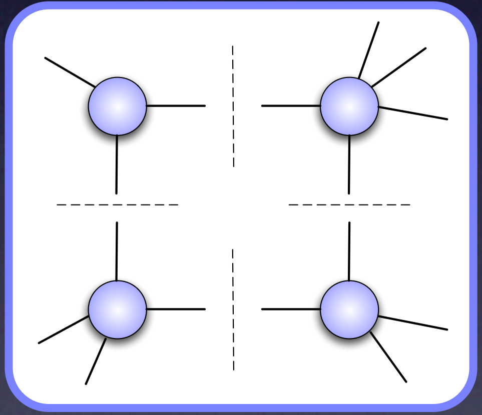
The NLO calculation of high multiplicity final states is very difficult

Traditional methods:

- ☺ Feynman diagram + Passarino Veltman style tensor reduction
- ☹ but size of resulting expression blows up with number of particles; also problems with numerical instabilities

Dedicated techniques for instabilities e.g. Denner and Dittmaier '05

Recent years have seen a revolution in the techniques used for NLO calculations



Modern methods:

- ☺ ***no*** Feynman diagrams. Instead use unitarity inspired ideas to reconstruct loop results from tree amplitudes
- ☺ lots of new ideas led to practical tools for LHC phenomenology at NLO [BlackHat, GoSam, Helac-NLO, MadLoop, Rocket, ...]

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

V + jets

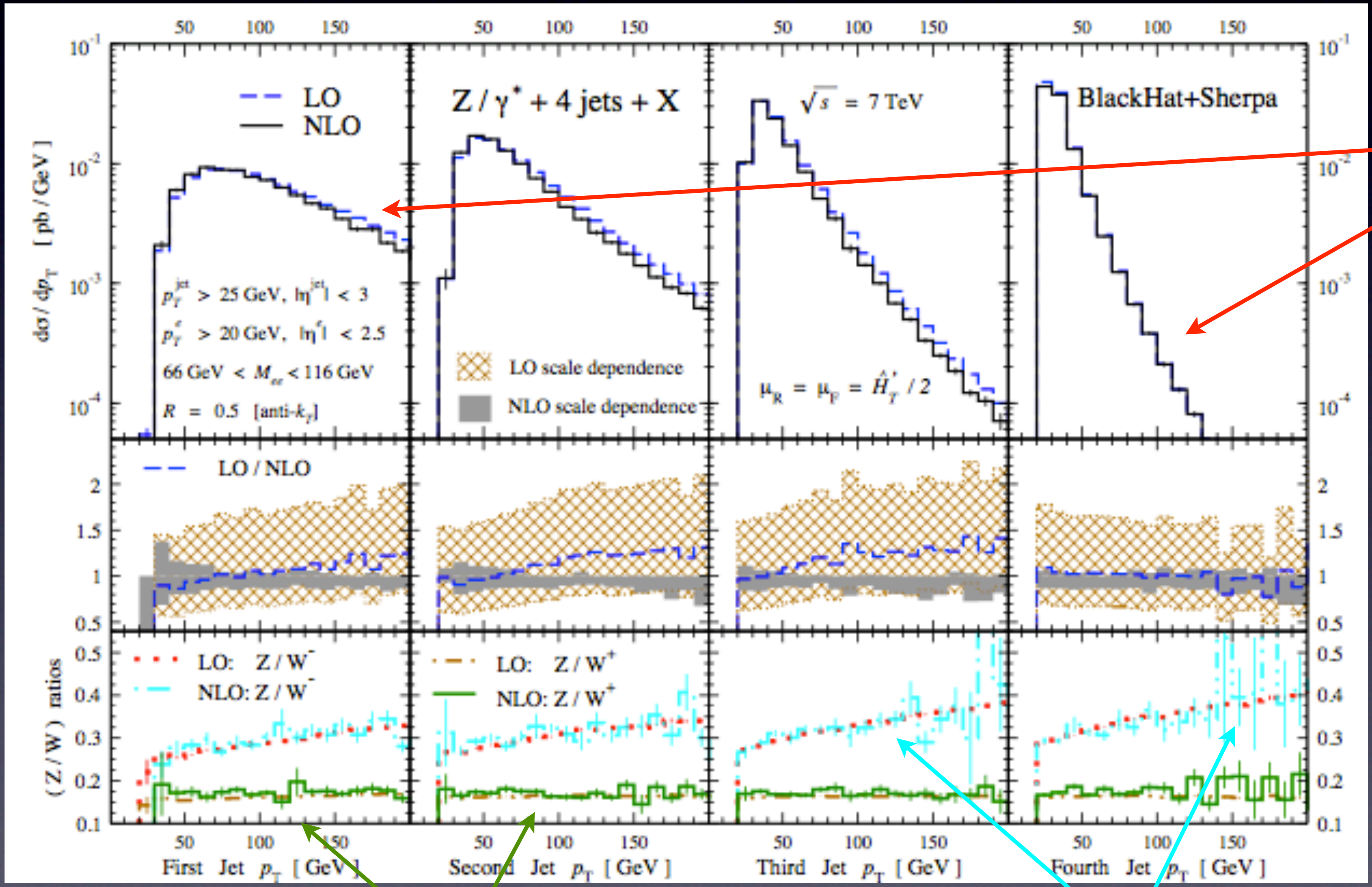
As a consequence of this theoretical progress a large number of complicated processes have been computed at NLO in recent years

- V + 1 jet 1983 — Ellis, Martinelli, Petronzio ’83; Giele, Glover, Kosower ’93
- V + 2 jets 2002 — Bern Dixon, Kosower ’97; Nagy, Trocsanyi ’98; Campbell, Ellis ’02
- VV + 1 jet 2007 — Campbell et al. ’07; Dittmaier et al ’07; Binoth et al. ‘09; Karg et al. ’10; Campanario et al ’10
- V + 3 jets 2009 — Ellis, Giele, Kunszt, Melnikov, GZ ’09; Berger, Bern, Dixon, Febres-Cordero, Forde, Gleisberg, Kosower, Ita ’09
- W^+W^- + bb 2010 — Bredenstein, Denner, Dittmaier, Kallwait, Pozzorini ’10; Bevilaqua, Czakon, van Hameren, Papadopoulos, Pittau, Worek ’10
- W^+W^+ + 2 jets 2011 — Melia, Melnikov, Rontsch, GZ ’11
- W^+W^- + 2 jets 2011 — Melia, Melnikov, Rontsch, GZ ’11
- V + 4 jets 2011 — Berger, Bern, Cordero, Dixon, Forde, Gleisberg, Kosower, Ita, ’10; Ita, Bern, Dixon, Febres-Cordero, Kosower, Maitre al ’11

Z + 4 jets at NLO

4 jets + $E_{T,miss}$: important background to SUSY searches

Ita et al. '11



additional jets steeper

LO/NLO not always flat

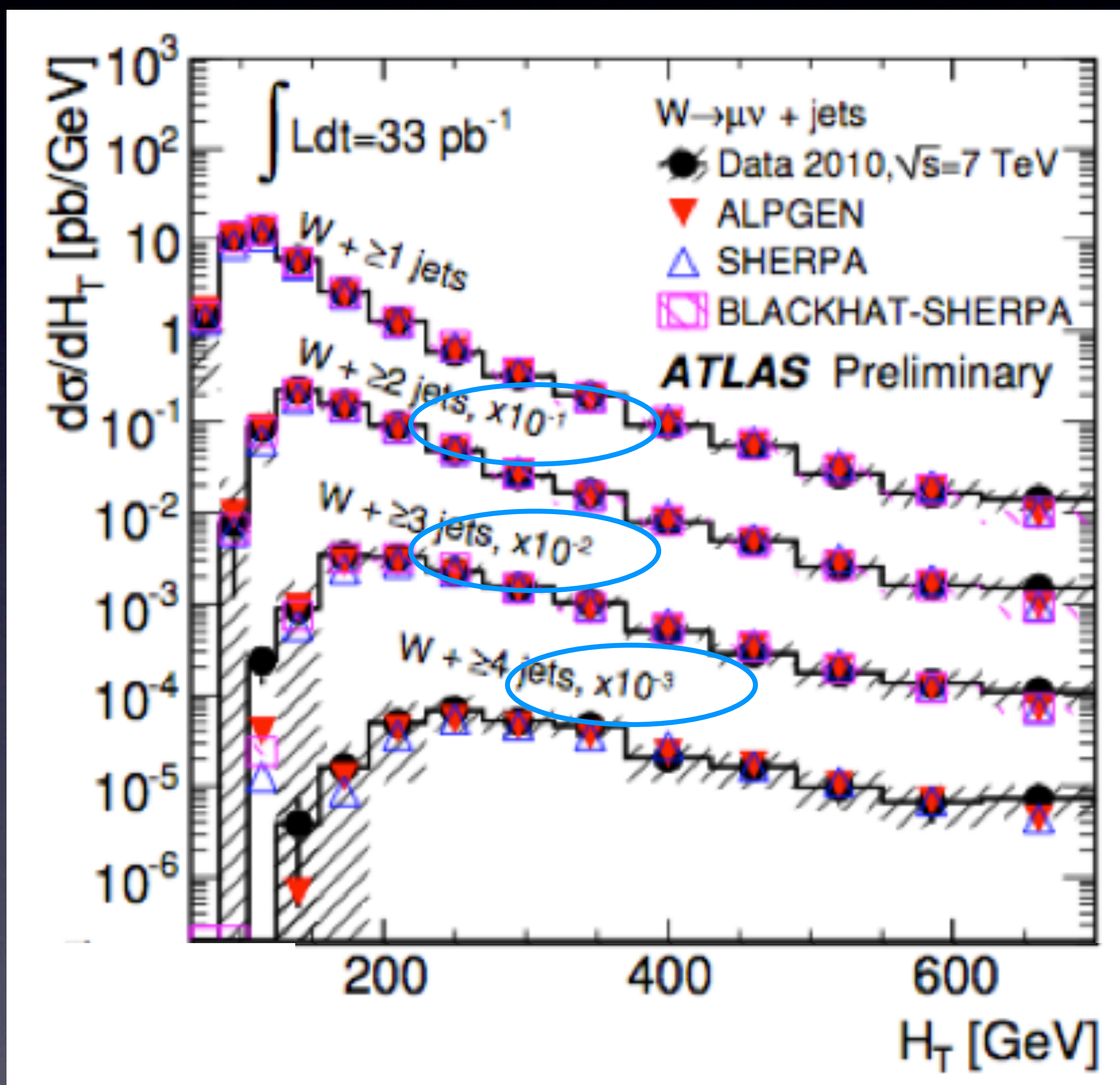
ratios: excellent PT control

Z/W^+: flat u(x)/u(x)

Z/W^-: u(x)/d(x) enhancement

W/Z with jets

H_T: total transverse energy in the event



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

At the LHC because of the large energy, W/Z production in association with jets very likely

At high H_T all jet-multiplicities contribute similar amounts

M. Mangano

NB: high H_T region of interest for various New Physics searches

Merging NLO and PS

NLO good for inclusive quantities, but gives a poor description of complex final states (exclusive measurements)

Combine best features: get correct rates (NLO) and hadron-level description of events (Parton Shower). Difficult to avoid double counting

Working frameworks

- MC@NLO
  Frixione & Webber '02 and later refs.
- POWHEG-BOX
  Nason '04 and later refs.
- POWHEG-method in SHERPA
  Hoche et al. '10

Processes implemented

- W/Z boson production
- WW, WZ, ZZ production
- inclusive Higgs production
- heavy quark production
- single top
- V + 1 jet
- dijets
- W + bb
- W^+W^+ + di-jets, ...
- ttj, ...

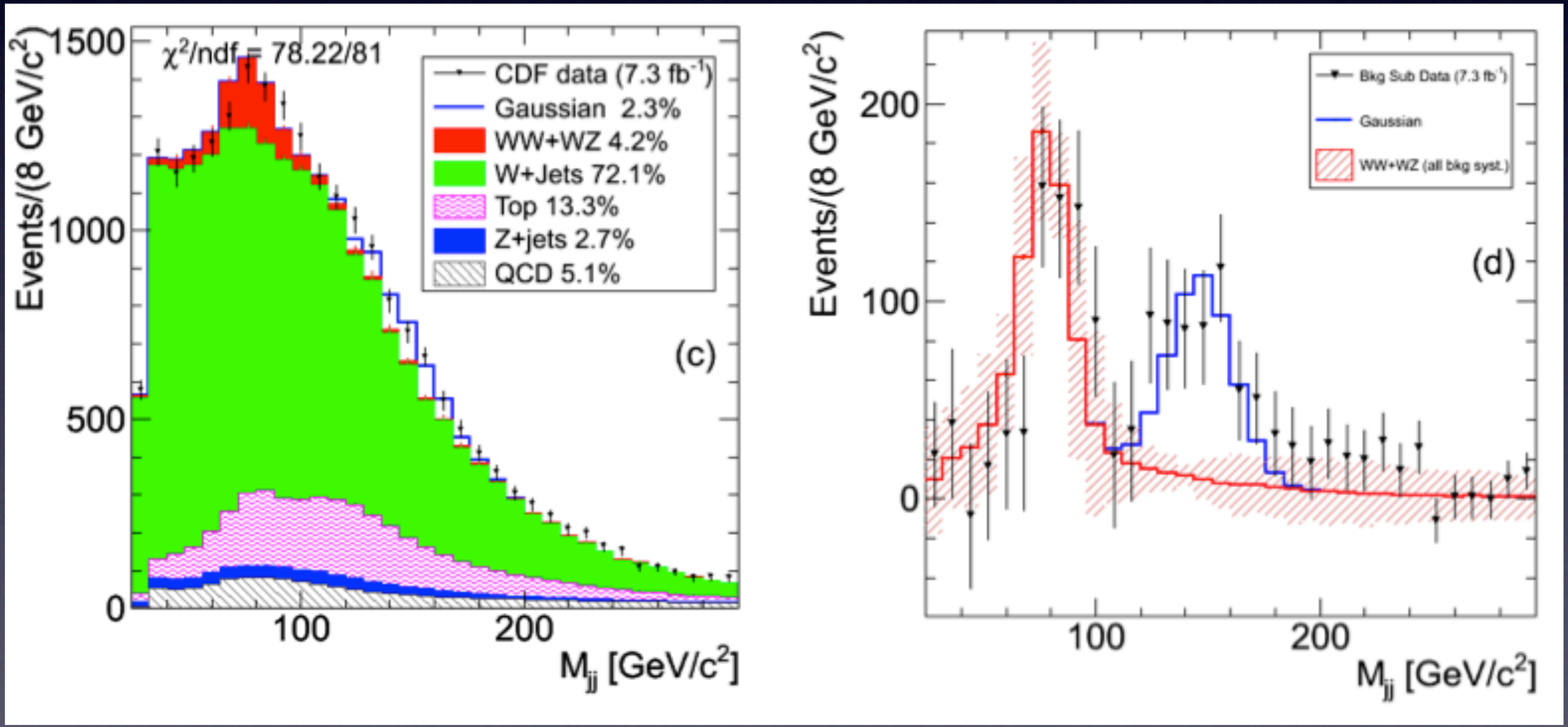
[...]

W + 2 jets in aMC@NLO

Recent development: aMC@NLO = automated event generation at NLO

Hirschi et al. 1104.5613

One application: re-analyze W + 2 jets excess seen by CDF



CDF 1104.0699

W + 2 jets in aMC@NLO

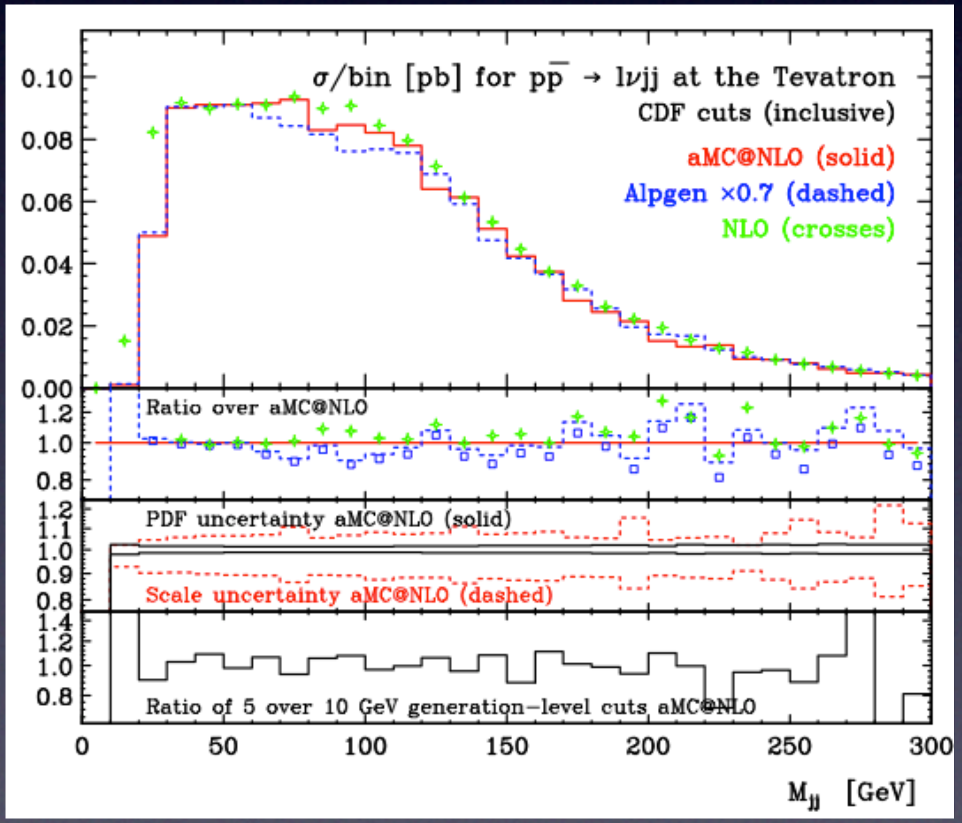
Recent development: aMC@NLO = automated event generation at NLO

Hirschi et al. 1104.5613

One application: re-analyze W + 2 jets excess seen by CDF

Frederix et al. 1110.5502

- CDF/D0 estimate Wjj background using LO Monte Carlo (LO+PS) re-weighted to NLO or to data
- With aMC@NLO: compute directly Wjj at the NLO+PS level. Check how well LO+PS or NLO describe the M_{jj} distribution



No enhancement over (N)LO or LO+PS in the mass range 130-160 GeV, but both theory uncertainty and "signal" are of the 10% level

V+jets: past, present, future

3 years ≈ time for a PhD

	3 years ago
Z/W	NNLO
V+1j	NLO
V+2j	NLO
V+3j	LO
V+4j	LO
V+5j	LO
VV	NLO
VV+1j	LO
VV+2j	LO
VV+3j	LO

V+jets: past, present, future

3 years ≈ time
for a PhD

	3 years ago	now
Z/W	NNLO	NNLO
V+1j	NLO	NLO+PS
V+2j	NLO	NLO(+PS)
V+3j	LO	NLO
V+4j	LO	NLO
V+5j	LO	LO
VV	NLO	NLO+PS
VV+1j	LO	NLO
VV+2j	LO	NLO(+PS)
VV+3j	LO	LO

V+jets: past, present, future

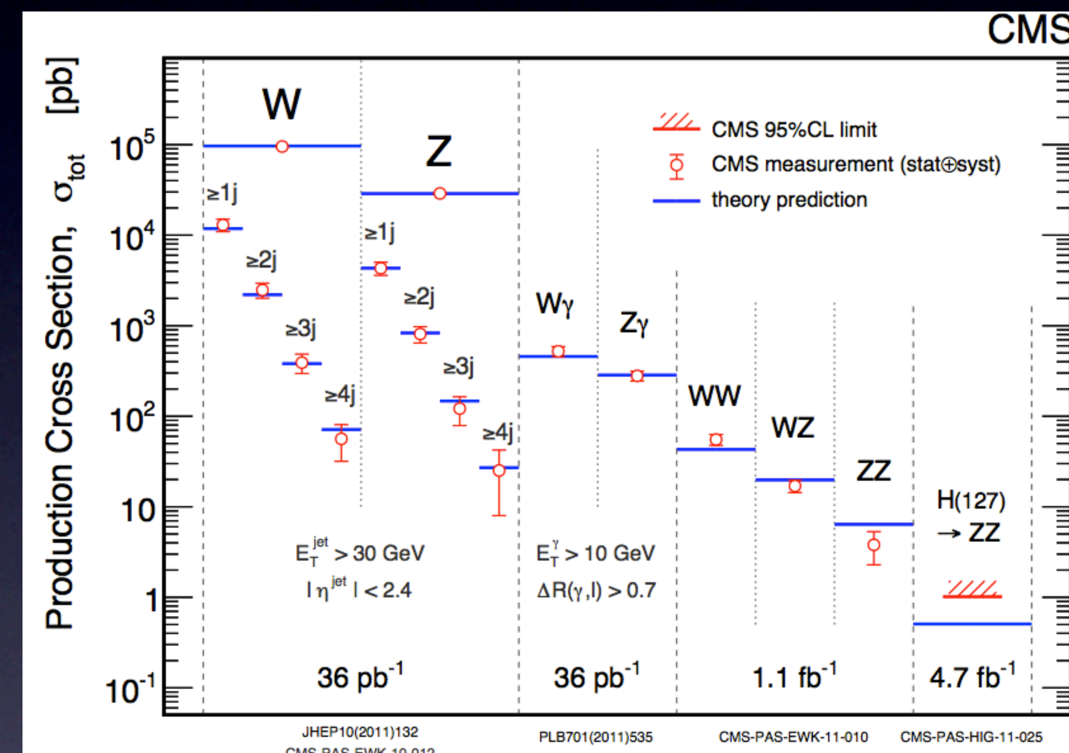
3 years ≈ time for a PhD

	3 years ago	now	in 3 years ?
Z/W	NNLO	NNLO	NNLO
V+1j	NLO	NLO+PS	NNLO
V+2j	NLO	NLO(+PS)	NLO+PS
V+3j	LO	NLO	NLO+PS ?
V+4j	LO	NLO	NLO
V+5j	LO	LO	NLO
VV	NLO	NLO+PS	NNLO
VV+1j	LO	NLO	NLO+PS
VV+2j	LO	NLO(+PS)	NLO+PS
VV+3j	LO	LO	NLO

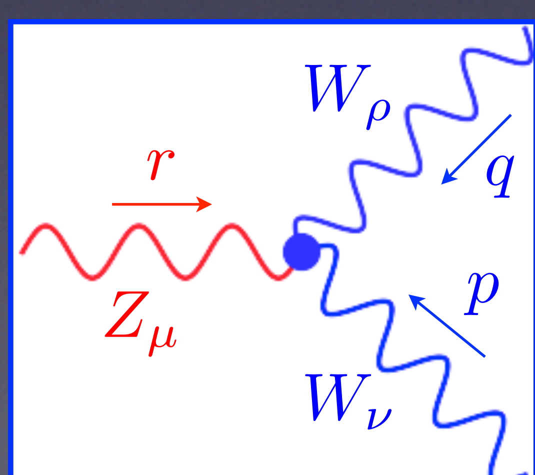
Diboson production

Other important benchmark processes are the pair-production of vector bosons: W^+W^-, $W^{+/-}Z$, ZZ

These are relatively simple processes (easy NLO) and clean experimentally. Can be measured accurately with enough statistics

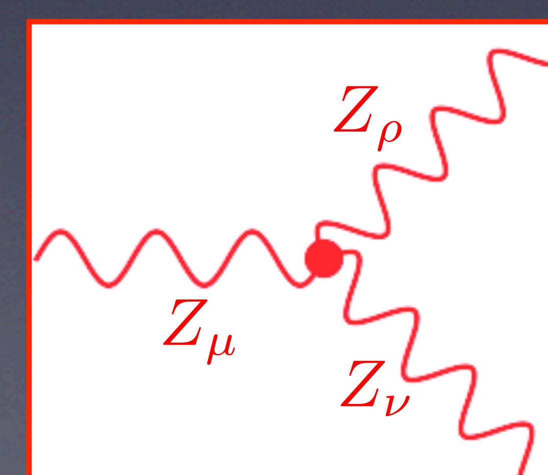


What makes these processes interesting per se is their sensitivity to anomalous triple gauge couplings (aTGC)



$$g_{ZWW} = i g_v [(p-q)_\mu g_{\nu\rho} + (q-r)_\nu g_{\mu\rho} + (r-p)_\rho g_{\mu\nu}]$$

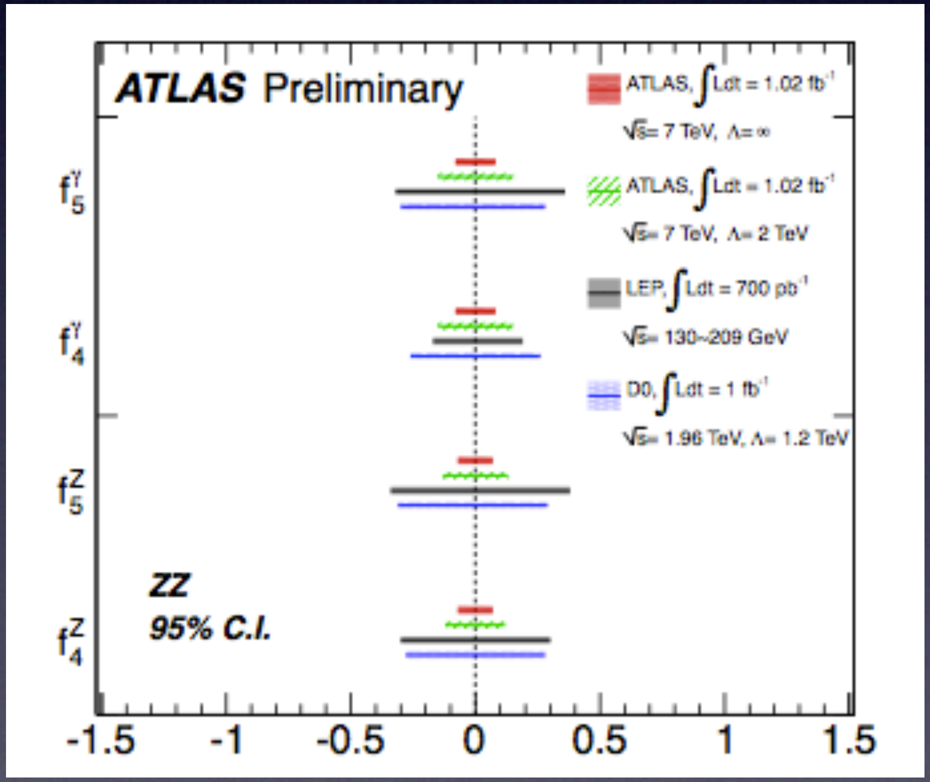
$$g_{ZZZ} = 0$$

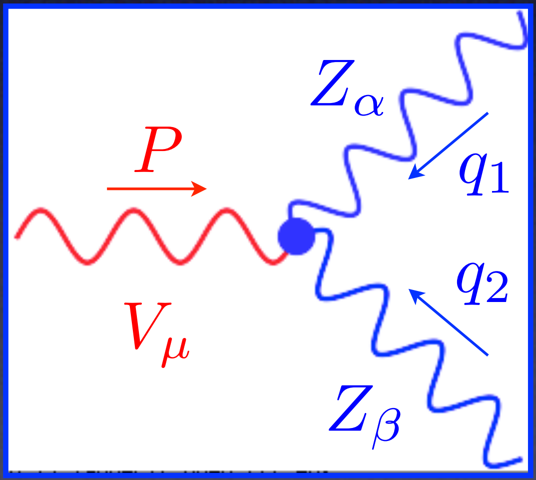


ZZZ and ZZγ aTGC

aTGC lead typically to enhanced production rate and to more energetic distribution of bosons and their decay products

Current best limits from LHC on CP violating (f4) and CP conserving (f5) neutral aTGC (ZZZ, ZZγ) (limits on other couplings available too)





$$g_{ZZV}\Gamma^{\alpha\beta\mu}_{ZZV} \propto e\left[if_4^V\left(P^\alpha g^{\mu\beta}+P^\beta g^{\mu\alpha}\right)+if_5^V\epsilon^{\mu\alpha\beta\rho}(q_1-q_2)_\rho\right]$$

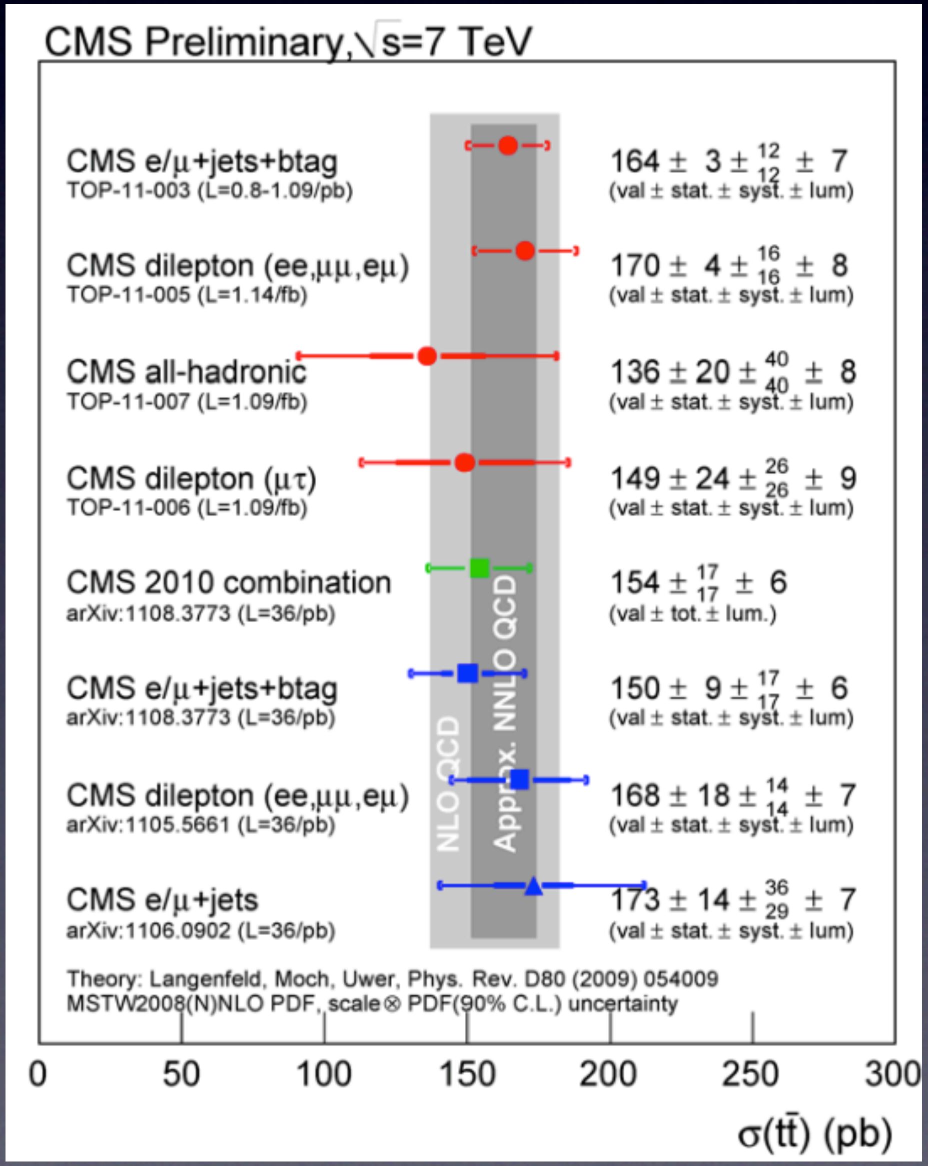
Top

Heaviest elementary particle known today. Large Yukawa coupling and prominent decay product in many new-physics models. A place where new physics is expected to show up.

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

The frontier of NNLO

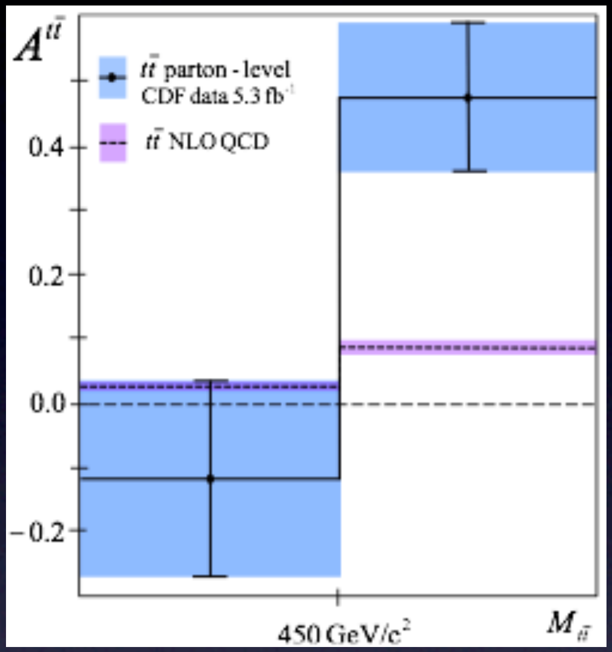
[. . .]



<u>Motivation for NNLO</u>

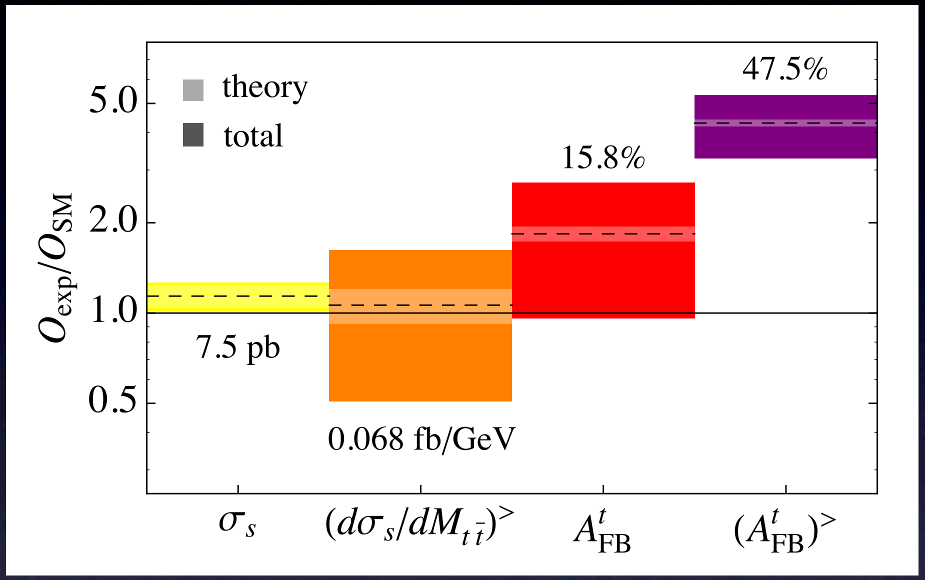
- constrain gluon pdf
- top mass from cross-section
- forward-backward asymmetry

Top charge asymmetry



CDF 1101.0034

Tension between sym. and asym.



Haisch & Westhoff '11

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

Asymmetry is 0 at LO, but theoretical arguments and partial higher orders suggest that NLO is robust under higher-order corrections

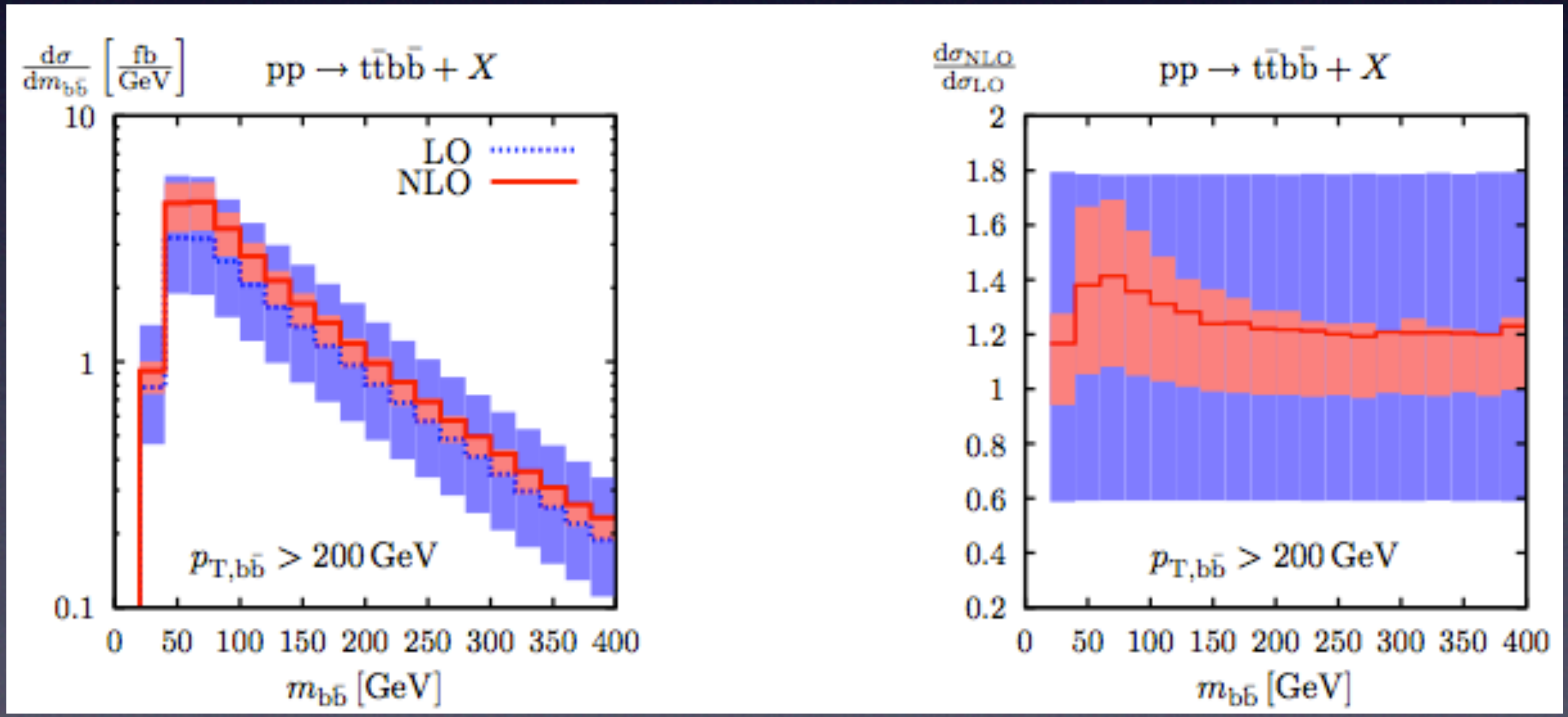
Almeida et al. 0805.1885; Melnikov and Schulze 1004.3284; Ahrens et al. 1106.6051 ...

Various new models try to explain data, but difficult to preserve good agreement with symmetric cross-section, like-sign top decays, ...

tt & bb production

ttbb and ttjj are very important backgrounds to tt+H with H → bb, best process to measure the top Yukawa coupling. Signal/background ratio = 1/10* require backgrounds to be known to better than 10%

LHC 14 TeV, boosted regime



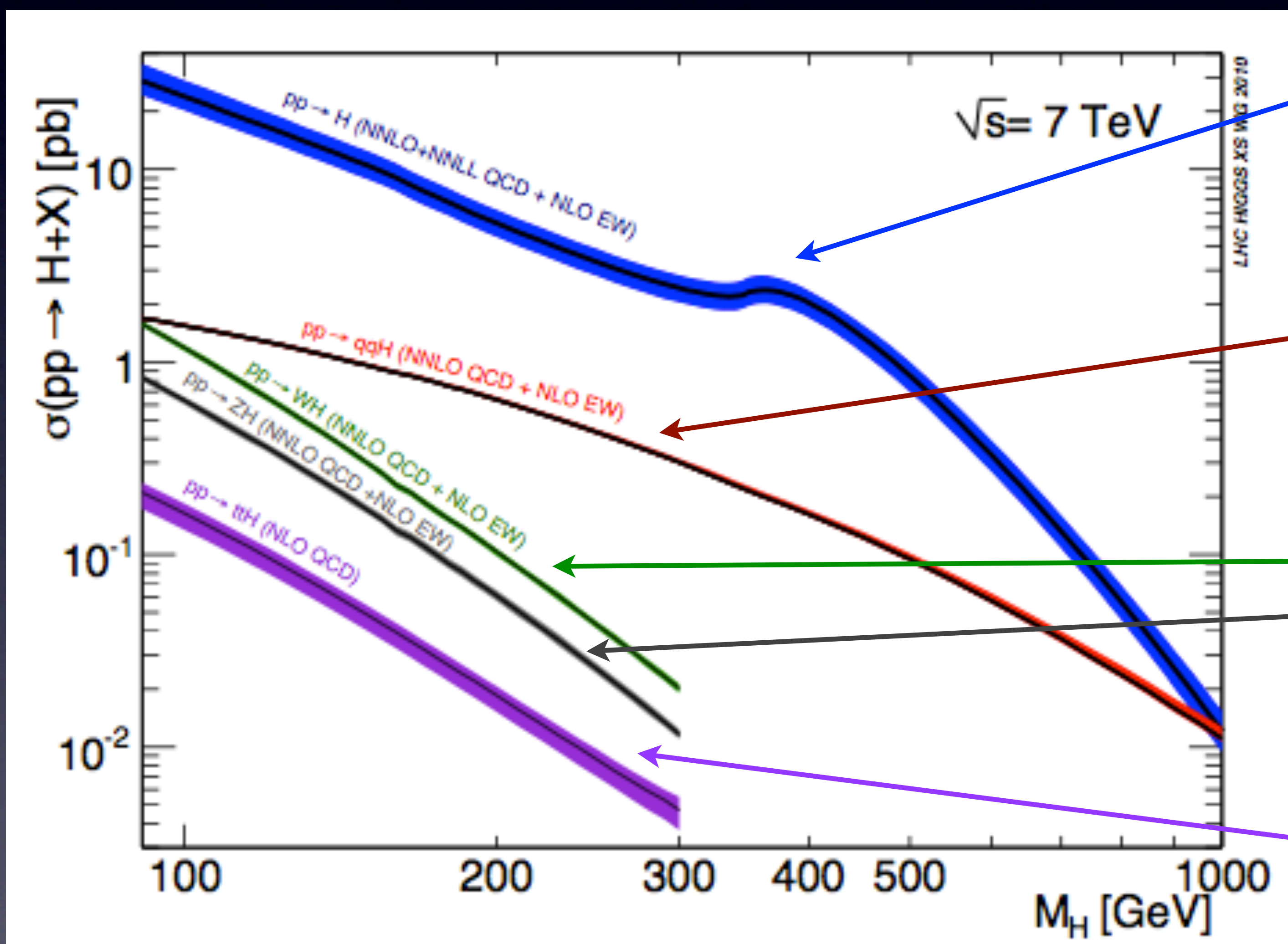
- reduction of uncertainty at NLO to 20%
- but shape distortion around M_{bb} = 80 GeV

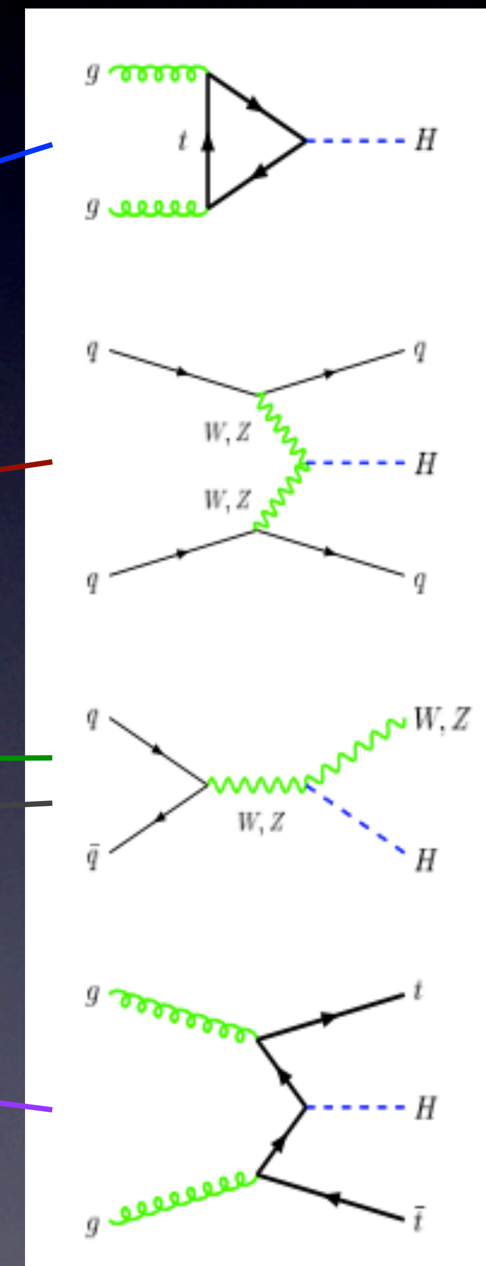
Bredenstein, Denner, Dittmaier, Pozzorini '08-'11
also: Bevilacqua et al. '09

(*) Signal to background improves to 1/3 with boosted techniques [Plehn, Salam, Spannovski '08]

SM Higgs production

Production modes





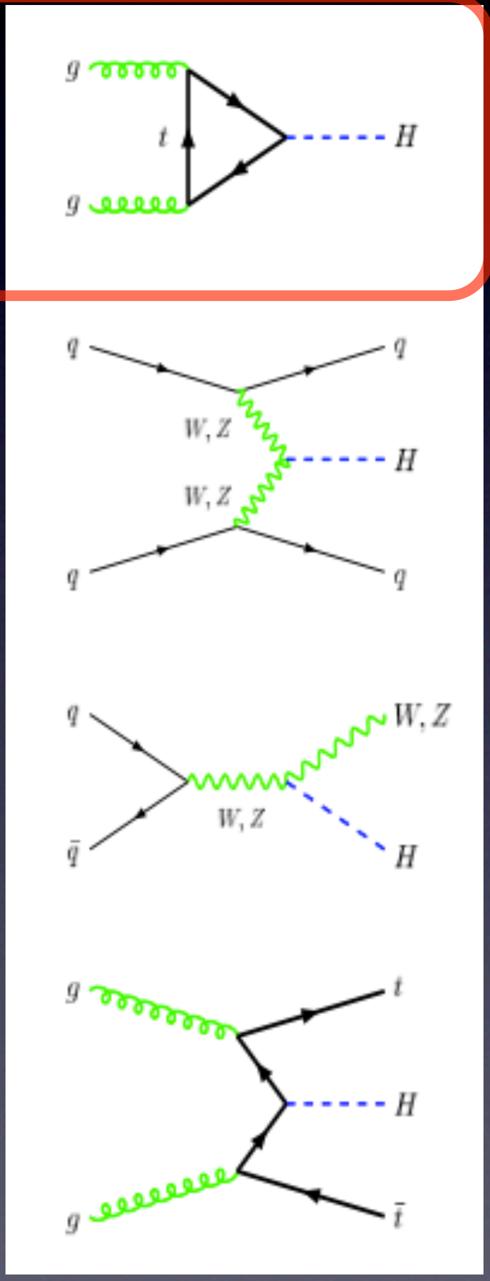
SM Higgs production

- largest mode
- most studied (NNLO,NLO+EW, NNLL ...)
- accuracy 20% ?

- distinctive tagging jets (apply VBF cuts)
- possibility to measure Higgs couplings
- NLO, partial NNLO. Accuracy 2-3% ?

- large background. Resurrected using boosted studies
- possibility to measure HWW and HZZ couplings
- NNLO production. Accuracy 2-5% ?

- re-analyzed using boosted studies
- would allow to measure Htt coupling
- difficult final state, large backgrounds (ttbb,ttjj)



see Handbook for LHC cross-sections: 1101.0593 and 1201.3084

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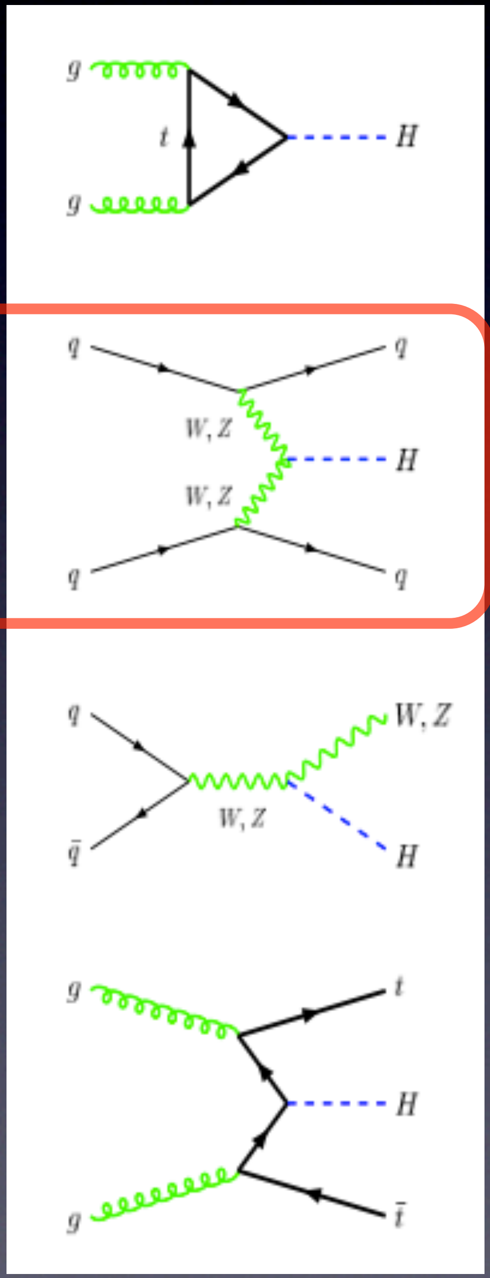

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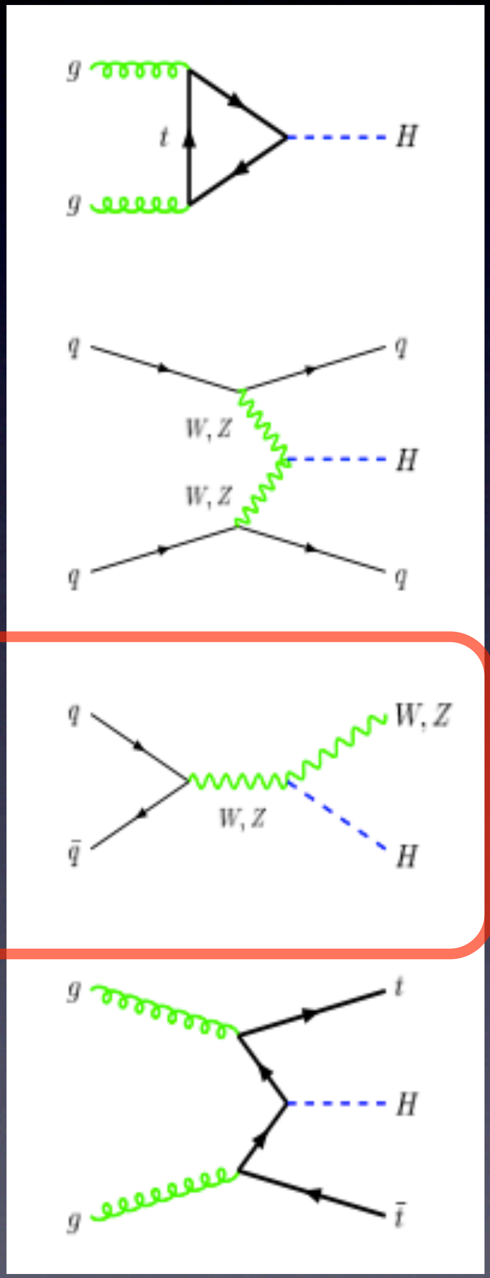

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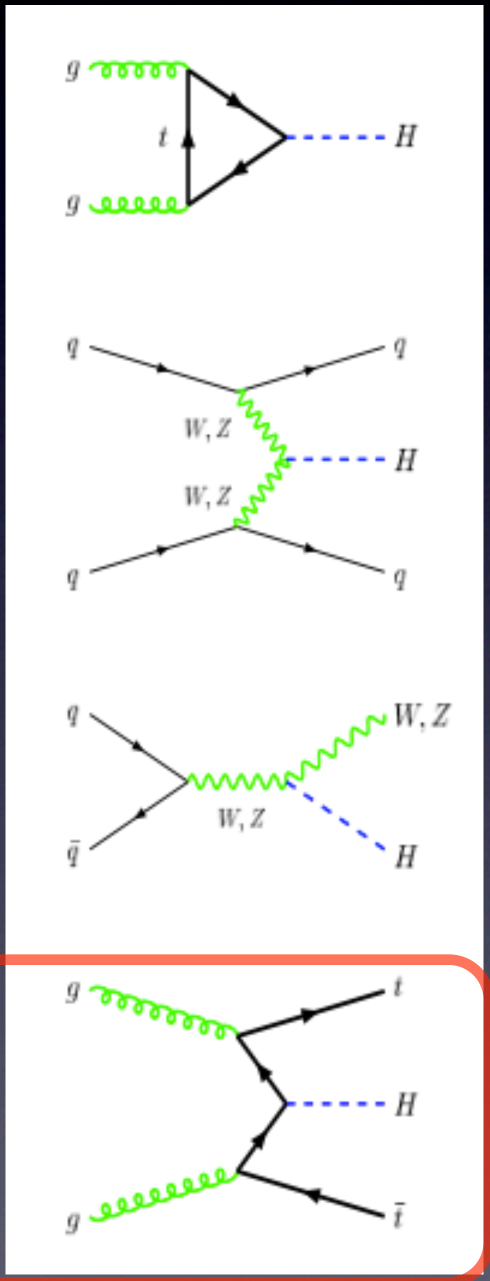

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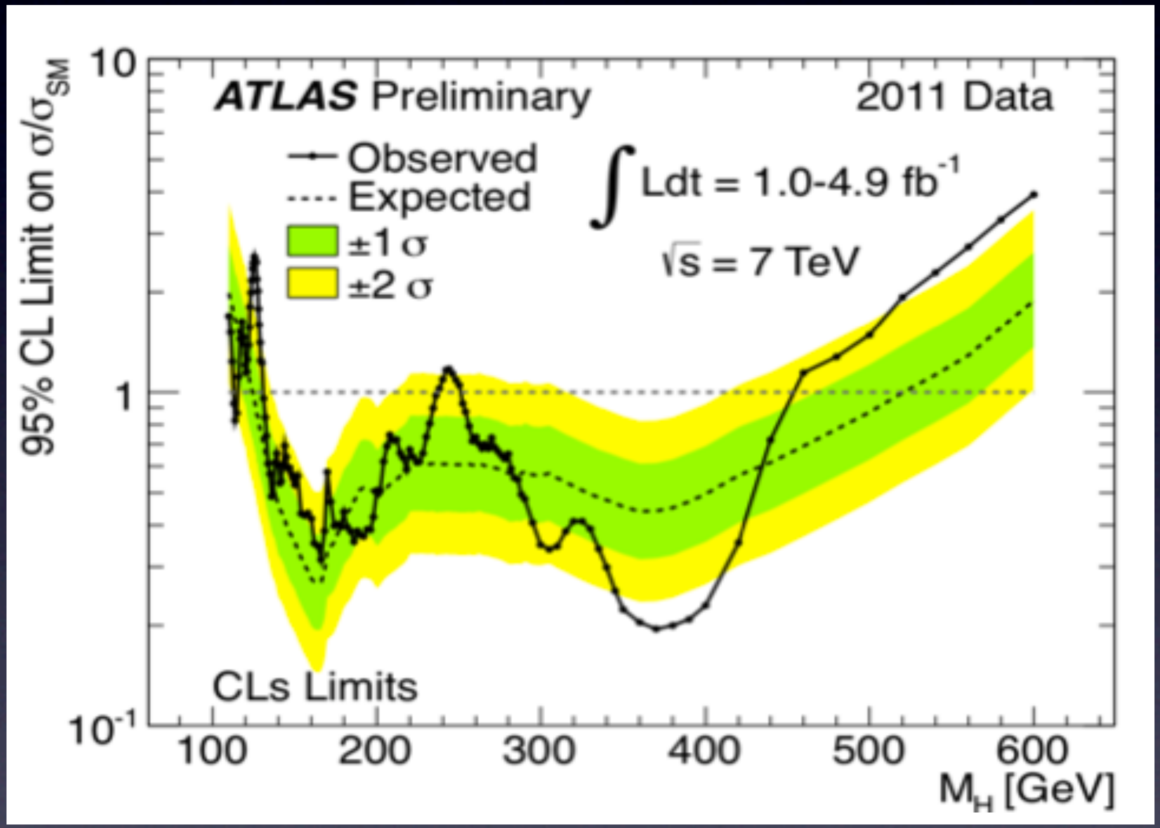
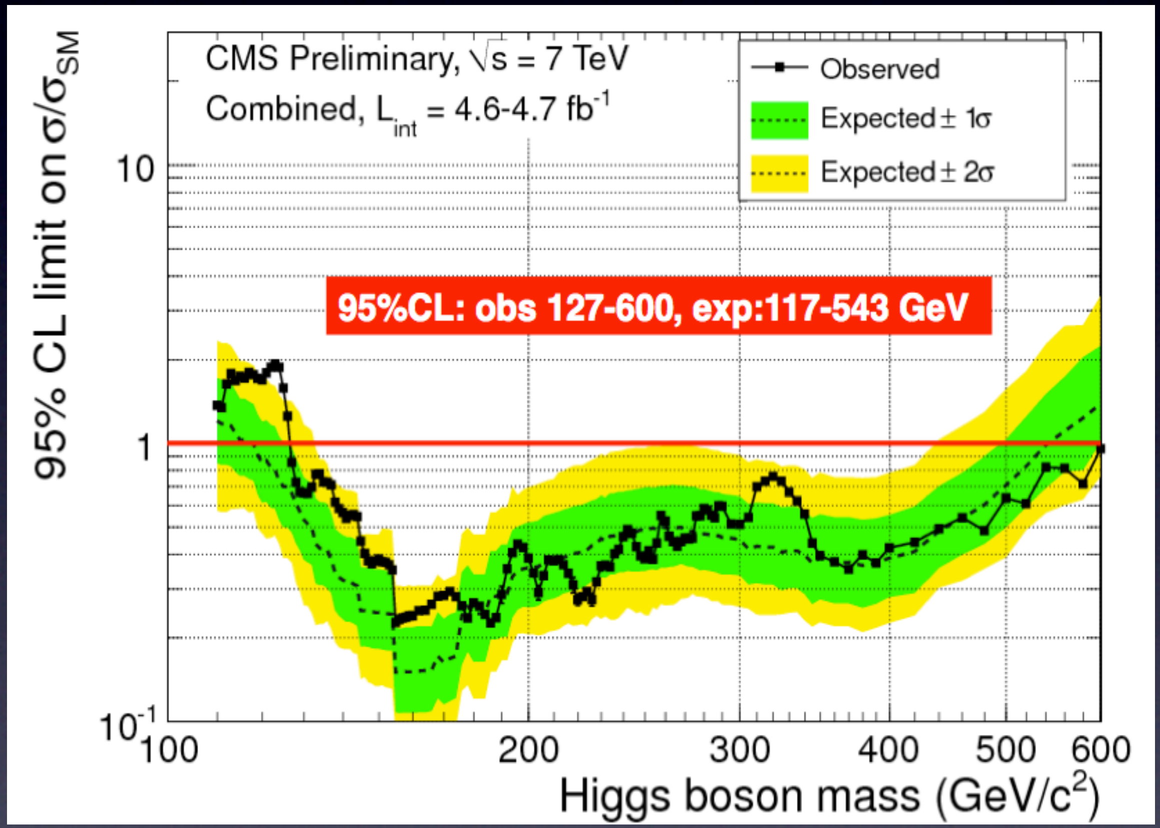
Higgs searches

As of December 13th (talks given at CERN by F. Gianotti and G.Tonelli)



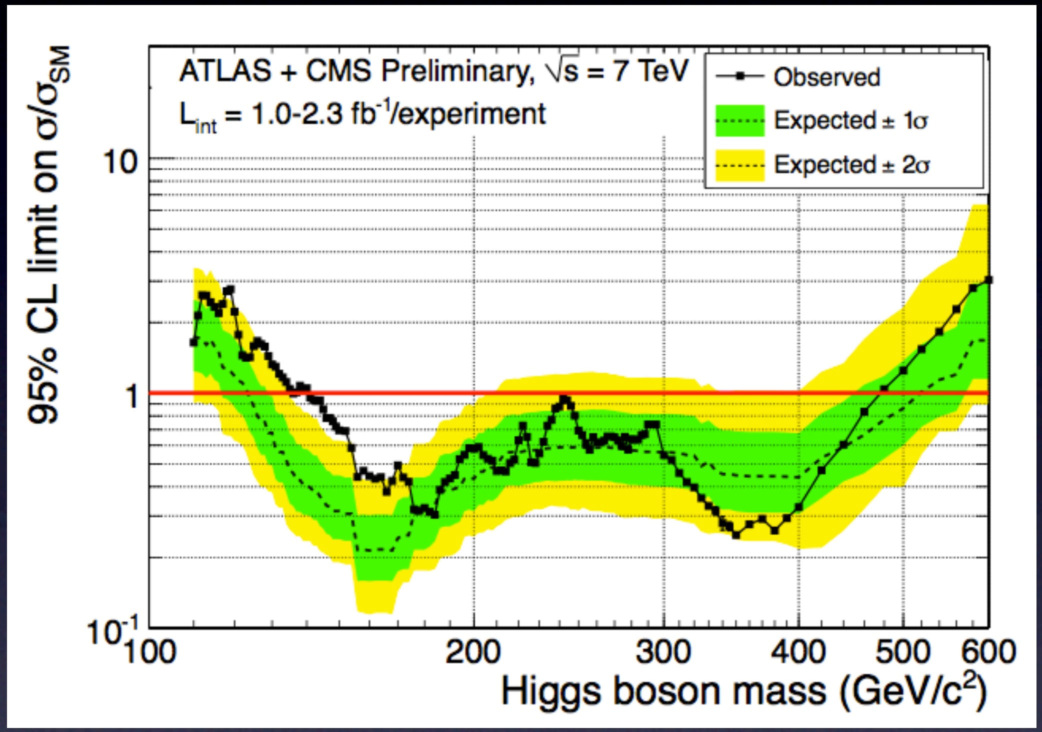


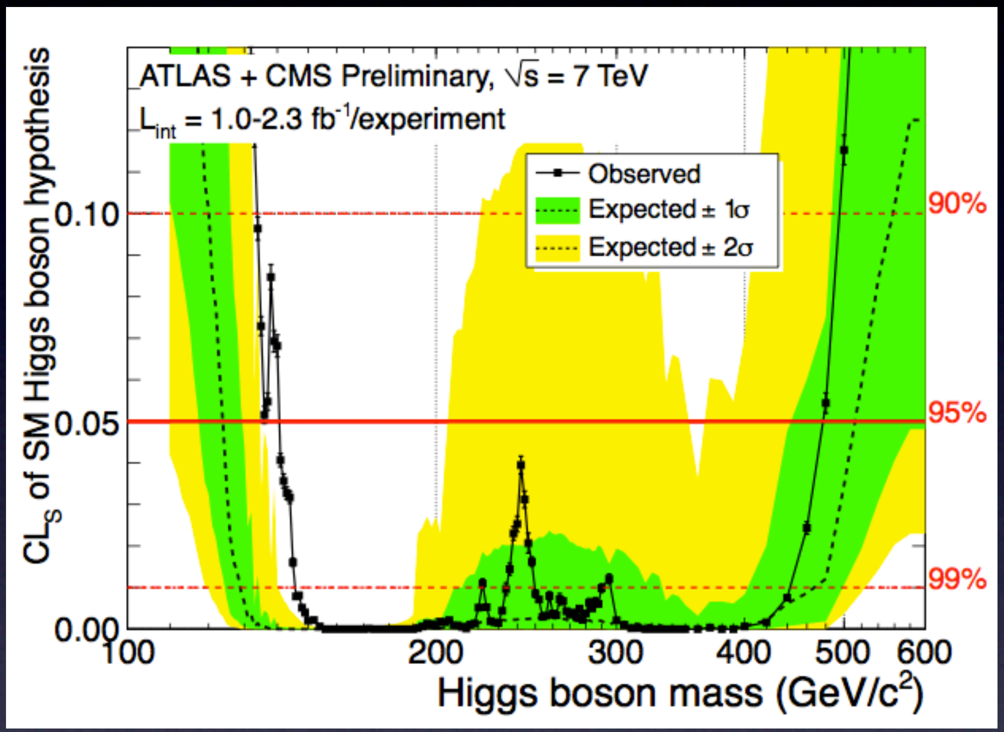
ATLAS: excess at 126 GeV. Higgs is in [115.5-131] GeV at 95% C.L.

CMS: excess around 124 GeV. Exclude [127-600]GeV at 95% C.L.

Combined Higgs searches

ATLAS-CONF-2001-157





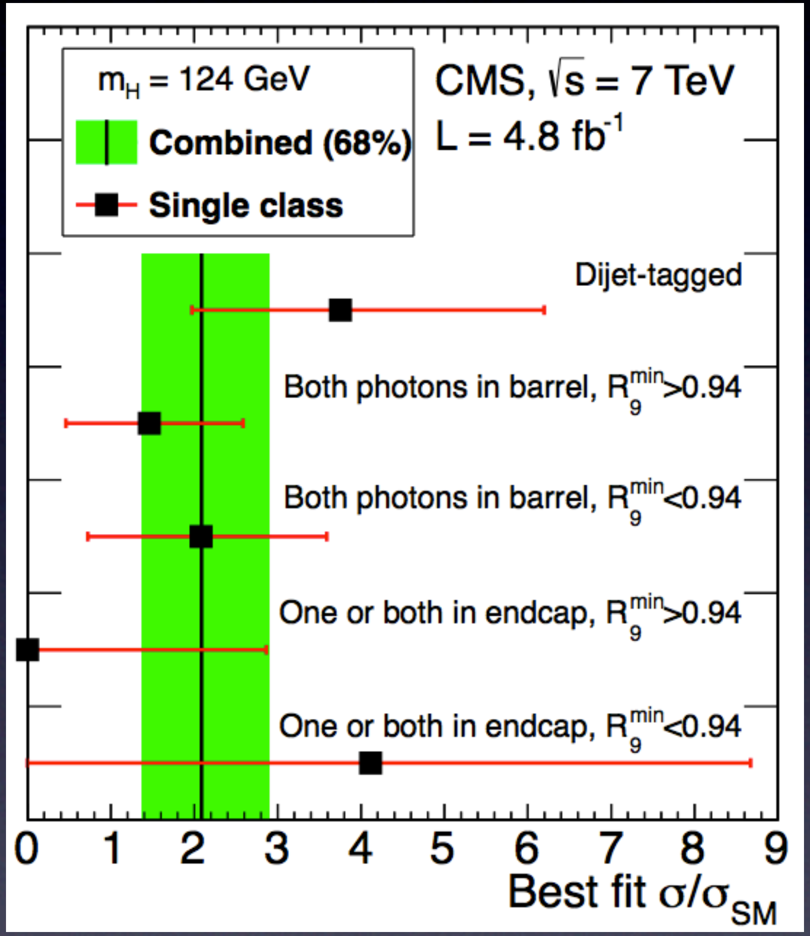
- slight tension between ATLAS and CMS preferred M_H gives only a modest significance to the largest excess (around 1.6σ)
- still statistically limited. More data needed. 2012 is the decisive year

Since 13th of Dec. many analyses published, but not much changed.
I'll mention here one just recent analysis of CMS that looks at $H \rightarrow \gamma\gamma$

One search in H → γγ

CMS 1202.1487

- CMS looks at the signal in five mutually exclusive regions
- splitting maximizes sensitivity: regions have different backgrounds and therefore benefit from different cuts
- one of the regions is VBF Higgs boson production "Dijet-tagged"
- outcome: M_H=124 GeV with 3.1(1.8)σ local (global) significance

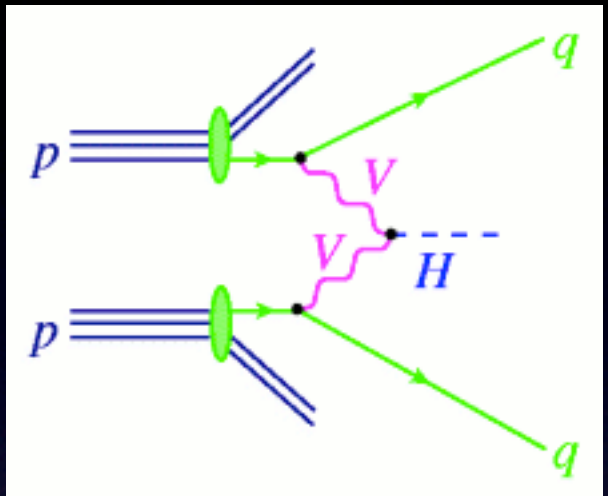


☛ per se not very significant, but further supports other measurements
☛ detection in H →γγ channel possible only since best fit gives $2\sigma_{SM}$
☛ interesting that this might be one of the first observation of VBF production. Need more studies of other SM VBF processes.

VBF processes

Suppressed color exchange between quark lines

- ➠ little jet activity in the central region
- ➠ in general modest QCD effects
- ➠ two forward (tagging jets)



Physics of Vector-Boson-Fusion (VBF) processes is very rich. It provides a unique possibility to measure gauge couplings and probe unitarity

A proper discussion would need a dedicated talk

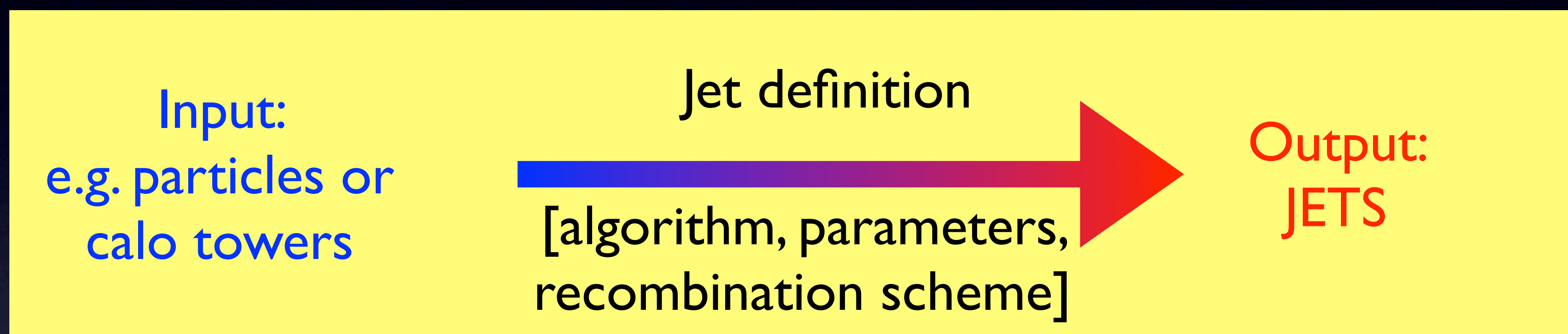
VBFNLO: flexible parton level Monte Carlo for VBF processes at NLO
The code is available at http://www-itp.particle.uni-karlsruhe.de/~vbfnloweb

Recent progress: NLO description of (NLO+PS available only in few cases)

- new processes: $jj\gamma$, WZj $W\gamma j$, $WW\gamma$ $ZZ\gamma$, $WZ\gamma$, $W\gamma\gamma$, $Z\gamma\gamma$, $\gamma\gamma\gamma$
- anomalous (quartic) couplings
- extension to MSSM

Jets

Jets are tools to attribute a simple structure to a more complicated event



They enter essentially any analysis at the LHC. Either you require jets, or you veto on jets, but you can't avoid talking about them, e.g.

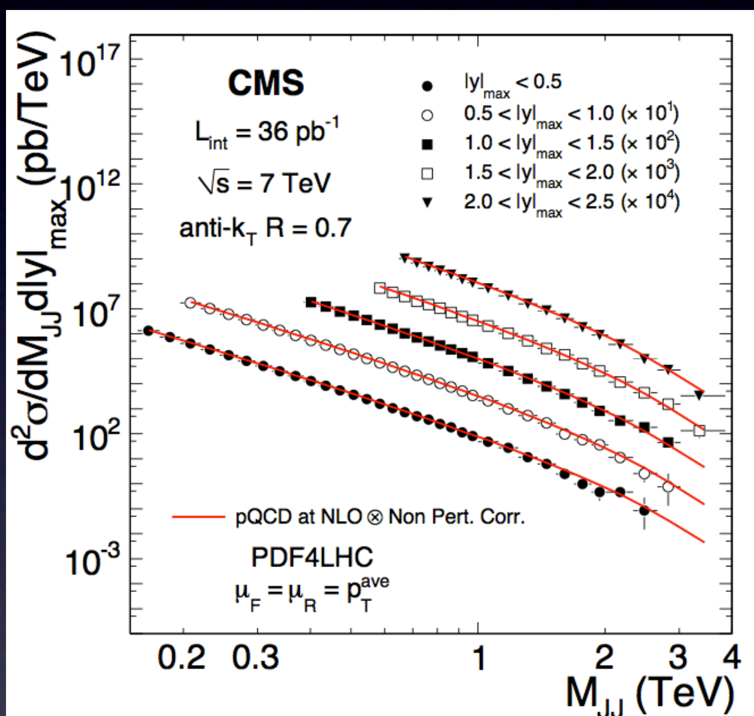
- top reconstruction
- mass measurements
- Higgs (jet-veto) and New Physics searches (multi-jets)
- instrumental QCD studies, e.g. inclusive-jet measurements
  $\Rightarrow$ important input for PDF determinations

Jet production

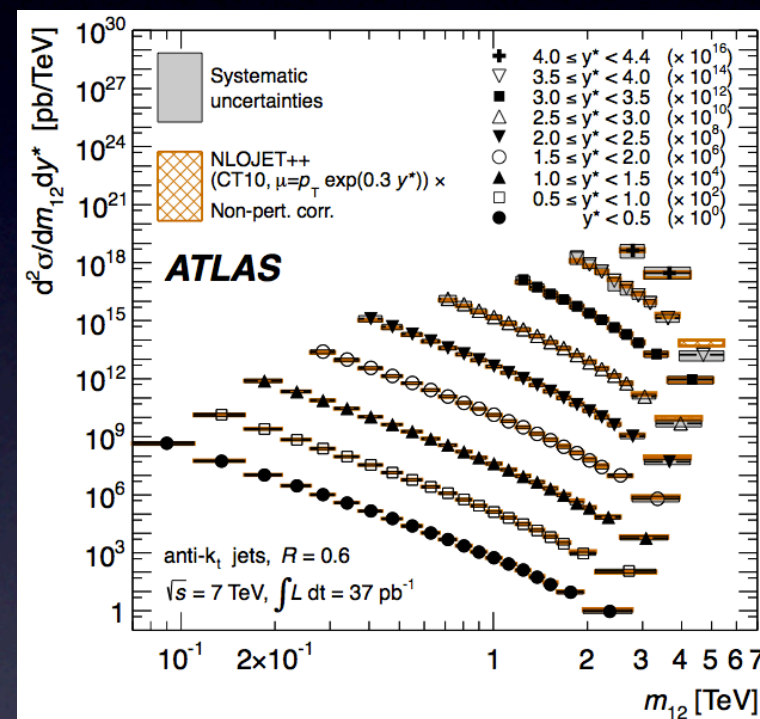
ATLAS and CMS adopted as default jet-algorithm: anti-k_t

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

Cacciari, Salam, Soyez ’08



CMS 1104.1693



ATLAS 1112.6297

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

~ 4 TeV

[Tevatron ~ 1 TeV]

Jet cross-sections probe many orders of magnitude (important constraints)

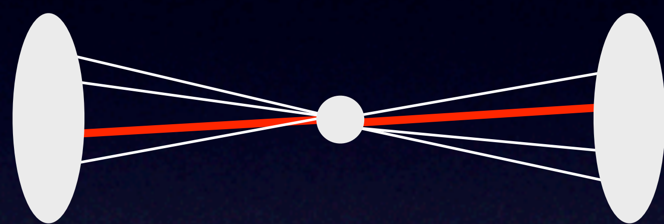
NB: Cambridge-Aachen algorithm more suitable for boosted studies

Dokshitzer et al. ’97

First time only infrared-safe algorithms are used systematically at a hadron collider

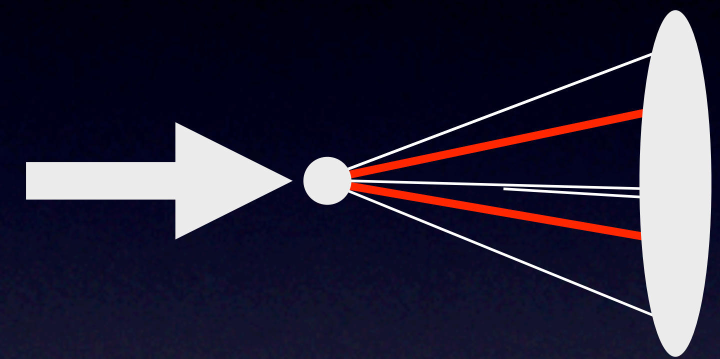
Boosted objects

Why are boosted processes potential discovery channels:



Non-boosted regime

Individual jets bare little information about the decaying particle



Boosted regime

Single fat jet catches all decay products of heavy particle

Typical procedure: construct a “fat jet” that contains all decay products of massive objects, then use clever methods to understand its structure

Intensive activity on fat jets: SM, t, SUSY, Z’, Extra-Dimensions ...

Writeup of Boost2010 workshop 1201.0008

Inside jets

Sophisticated analysis of structure of jets

- boosted massive objects ➛ fat jets, with internal structure
- look inside a fat jet ➛ jet-substructure
- eliminate underlying event/pile-up from jet ➛ jet-grooming
  - filtering: e.g. undo last recombinations and keep only few sub-jets
  - pruning: take a jet of interest and re-cluster it and veto asymmetric wide angle recombinations
  - trimming: discard regions in a jet with too little energy

\+ big gain in sensitivity over traditional methods

− need high luminosity for boosted regime and kinematical cuts, but effect of pile-up not fully studied yet

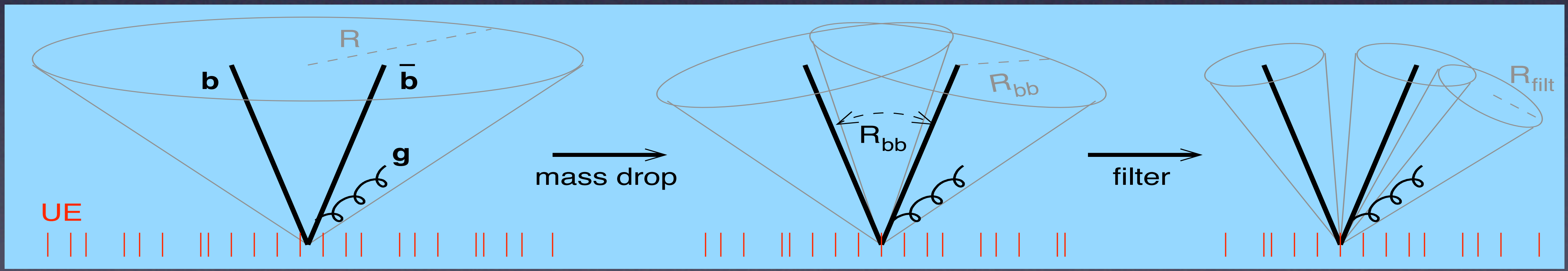
Almeida, Butterworth, Cacciari, Chen, Davison, Ellis, Falkowski, Han, Katz, Kim, Kribs, Krohn, Lee, Martin, Nojiri, Perez, Plehn, Raklev, Rehermann, Roy, Rojo, Rubin, Salam, Shelton, Sreethawong, Son, Soyez, Sung, Thaler, Tweedie, Schwartz, Seymour, Soper, Spannowsky, Sterman, Virzi, Wang, Zhu, ...

VH rescued ?

VH(bb) is hard because of overwhelming QCD backgrounds (Wbb, Zbb, Wjj, tt,bb+X ...). Considered impossible at the LHC.

Central idea: require high-p_T W and Higgs boson in the event

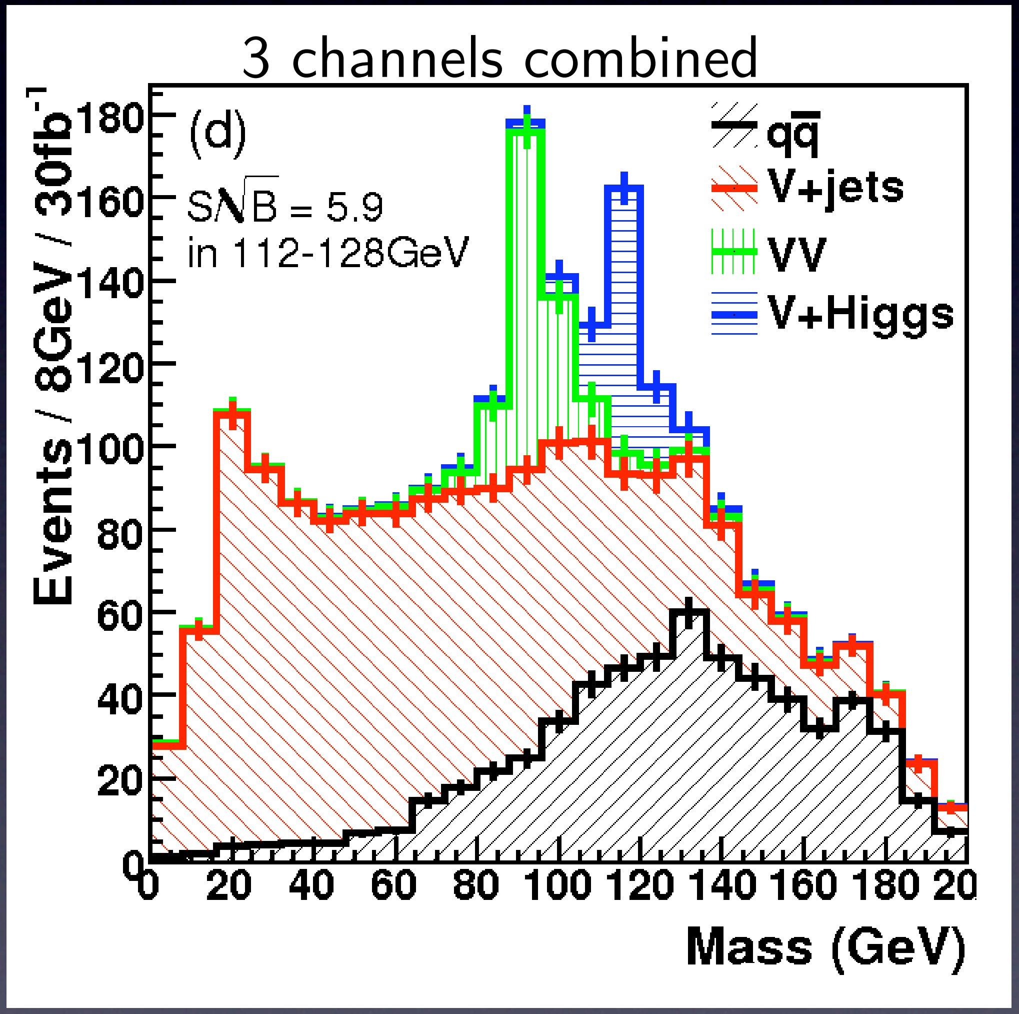
- leads to back-to-back events with two b-quarks in the same jet
- then exploit the specific pattern of H → bb vs g → gg, q → gg
- and try to clean the event



1. cluster the event with e.g. CA algo and large-ish R
2. undo last recomb: large mass drop + symmetric + b tags
3. filter away the UE: take only the 3 hardest sub-jets

VH rescued ?

Mass of the three hardest sub-jets:



- with common & channel specific cuts:
  p_{tV}, p_{tH} > 200GeV , ...
- real/fake b-tag rate: 0.7/0.01
- NB: very neat peak for WZ (Z → bb)
  Important for calibration

Butterworth, Davison, Rubin, Salam '08

5.9σ at 30 fb^{-1}: VH with H → bb recovered as one of the best discovery channels for light Higgs ?

Boosted methods at use

Example relevant for WH(→bb)

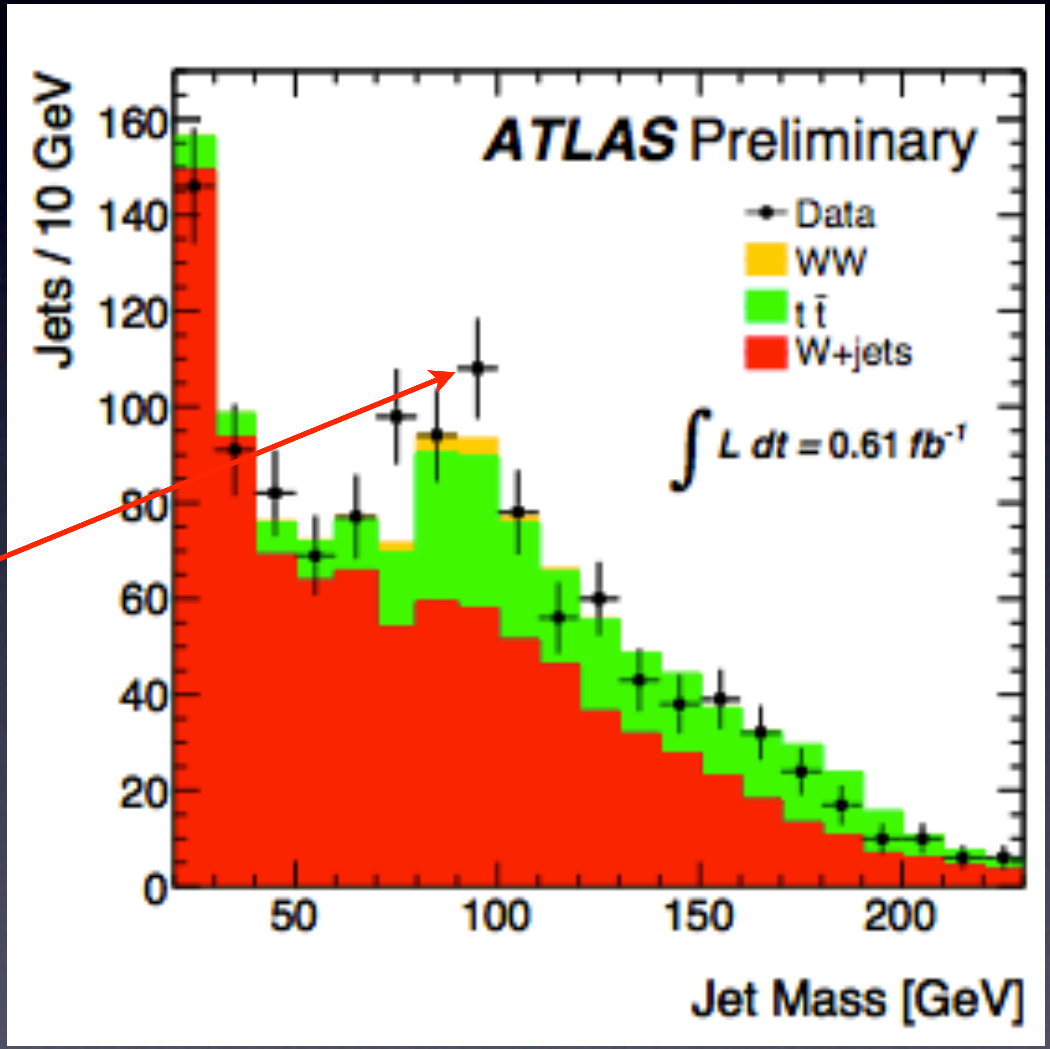
ATLAS require

- one lepton
- missing energy
- a fat jet (R=1.2)
- mass-drop
- use filtering techniques on jet

Z peak evident. Very promising

Expect many new results with boosted techniques at higher statistics soon

Single jet hadronic mass in W+1j



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

Conclusions

- physics at the LHC extremely rich: spans from most precise measurements (DY) to searches with highest reach (aTGC)
- experimental program at the LHC supplemented by robust theoretical predictions (NLO, NLO-QCD+EW, NNLO, NLL ...) + clever new ideas and techniques (e.g. new jet-algorithms, boosted techniques, matching ...)
- clear, successful effort to produce predictions and public codes that have the flexibility required for today's sophisticated experimental analysis
- after just one year of running at the LHC in some cases physics starts being dominated by theory and pdf errors
- a real challenge for theorists to keep up with high experimental precision
- LHC has triggered lots of new ideas whose potential is yet to be fully exploited