# QCD and Tools for the LHC

Giulia Zanderighi

University of Oxford & STFC

8$^{th}$ Vienna Central European Seminar, Particle
on
*Particle Physics and Quantum Field Theory*

# Open questions

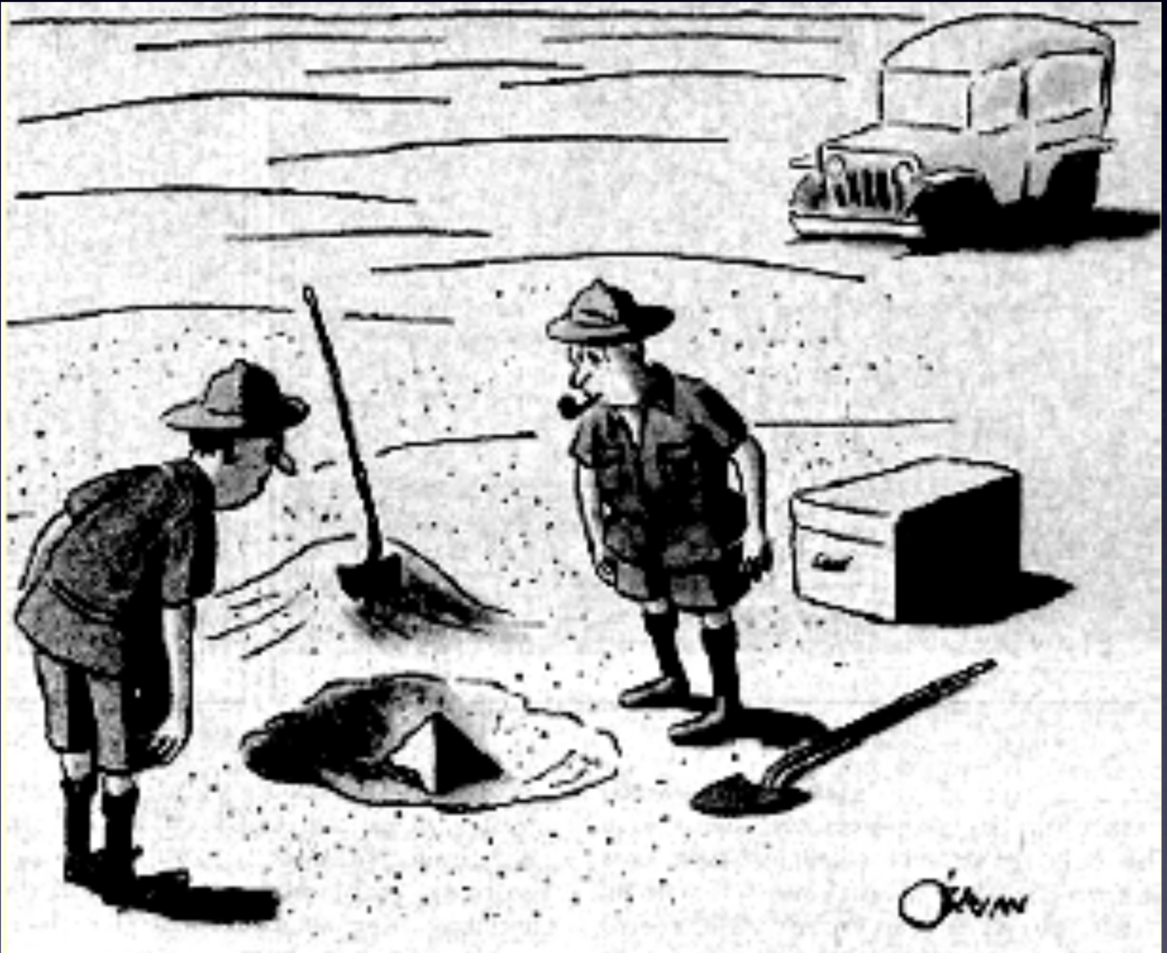
Today, we face many open questions some driven by experimental data (they have an answer), most driven by theoretical curiosity and ambition (they might have an answer)

*My* top 10:

1. What is the dynamics of electroweak symmetry breaking ?
2. What is the nature of dark matter ?
3. What causes the hierarchy of fermion masses and mixings ?
4. Why three generations ?
5. At what scale are neutrino masses set ?
6. What resolves the strong CP problem ?
7. What is the origin of the matter-antimatter asymmetry ?
8. What physics is associated with the vacuum energy ?
9. How does gravity enter the picture ?
10. Are these the good questions to ask ... ?

# LHC & the big questions

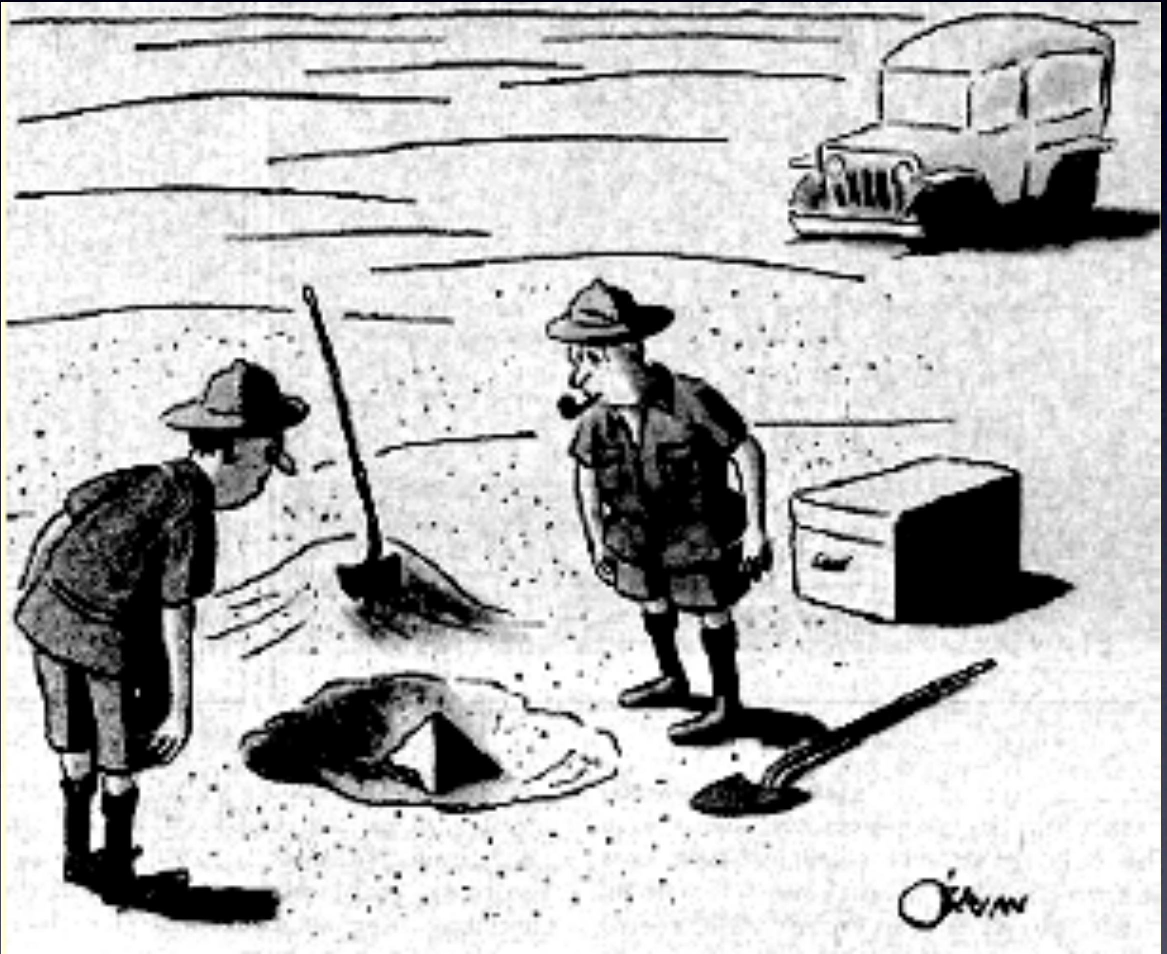
- We hope to be at the verge of big changes, whose depth we can not assess yet



*"This could be the discovery of the century. Depending, of course, on how far down it goes"*

# LHC & the big questions

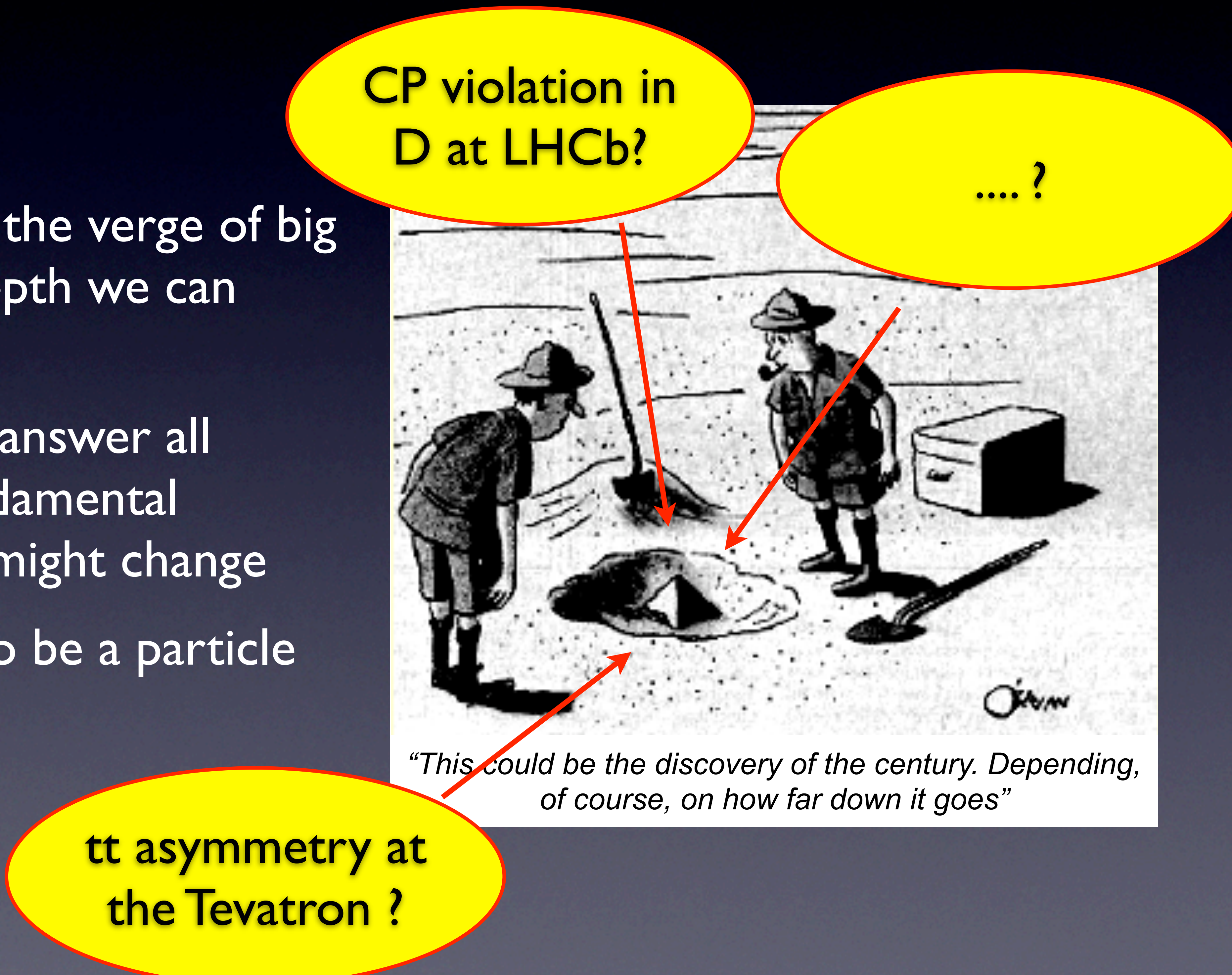
- We hope to be at the verge of big changes, whose depth we can not assess yet
- The LHC will not answer all questions, but fundamental questions we ask might change



*"This could be the discovery of the century. Depending, of course, on how far down it goes"*

# LHC & the big questions

- We hope to be at the verge of big changes, whose depth we can not assess yet
- The LHC will not answer all questions, but fundamental questions we ask might change
- It is a great time to be a particle physicist




*"This could be the discovery of the century. Depending, of course, on how far down it goes"*

# LHC status

2010 data: ~45$pb^{-1}$

- commissioning and calibration
- O(100) ATLAS and CMS paper [~55 ATLAS + ~65 CMS]
- all major Standard Model processes have been re-established
  (inclusive jet, inclusive photon, charged hadrons, heavy mesons, electroweak and top processes, single top, di-bosons ... )
- entering new territory

2011 data [till end Sept]: >5 $fb^{-1}$

- precision measurements
- searches with sensitivities already far exceeding those of LEP and Tevatron

(Higgs, SUSY, Heavy bosons W' and Z', leptoquarks, long-lived particles ... )

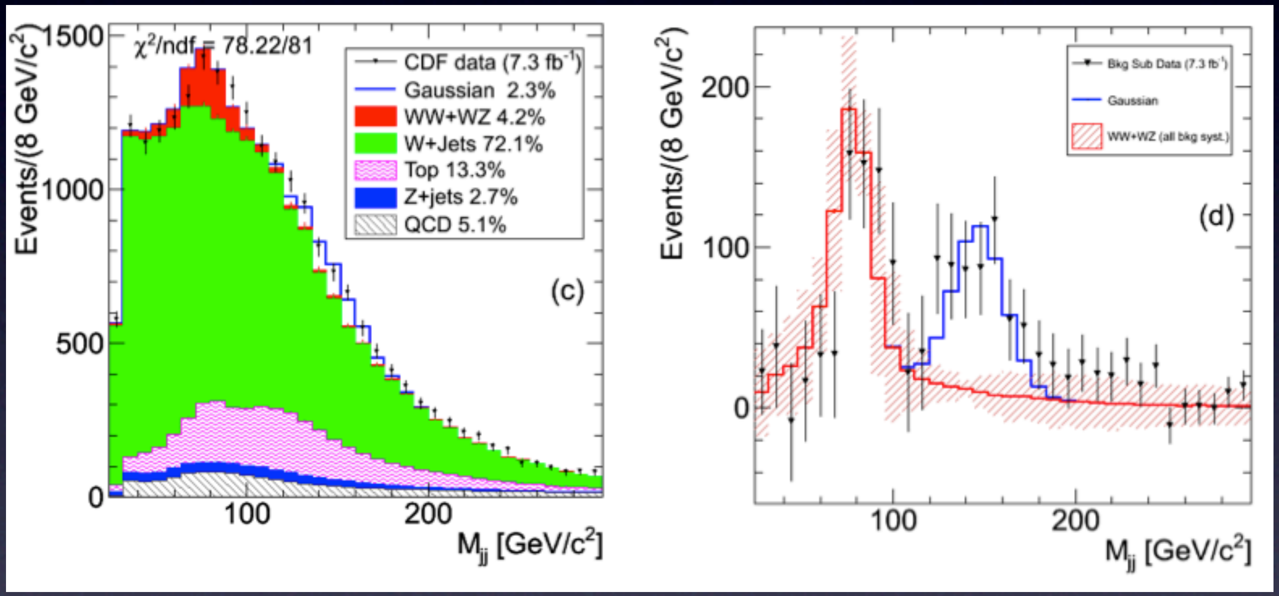
*The 2010 - 2011 run was much more successful than any theorist expected!*

# Meanwhile in Batavia

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

CDF col. 1104.0699

Update to include 7.3fb$^{-1}$ $\Rightarrow$ 4.1 $\sigma$



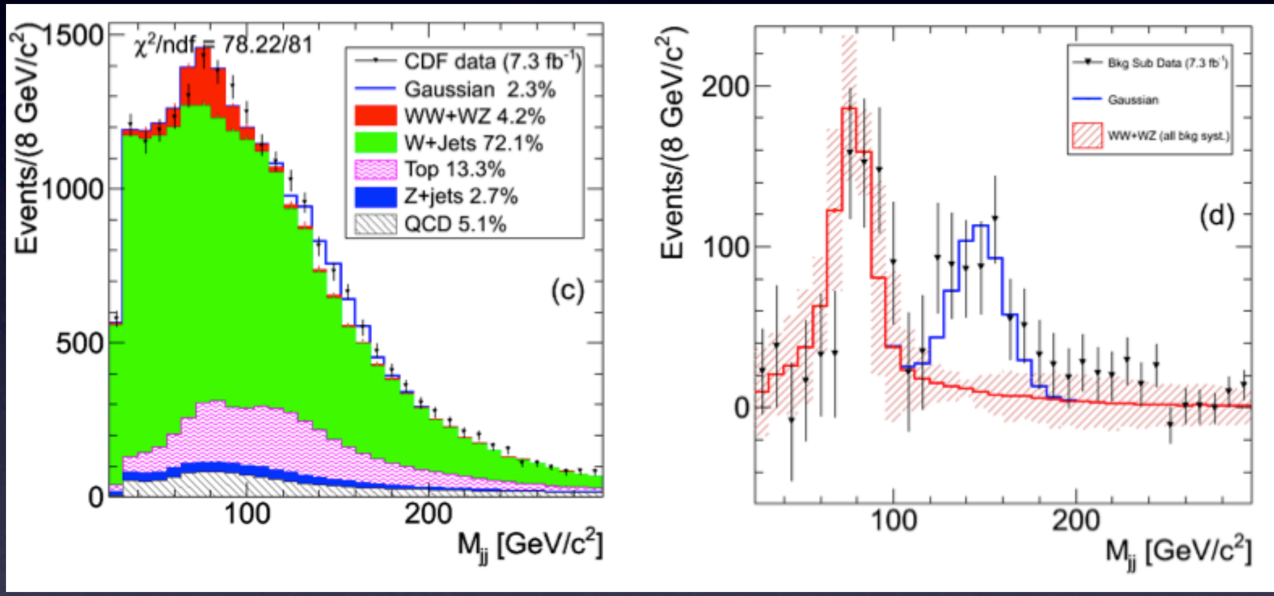

http://www-cdf.fnal.gov/physics/ewk/2011/wjj

# Meanwhile in Batavia

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

CDF col. 1104.0699

Update to include 7.3fb$^{-1}$ $\Rightarrow$ 4.1 $\sigma$




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

Since then

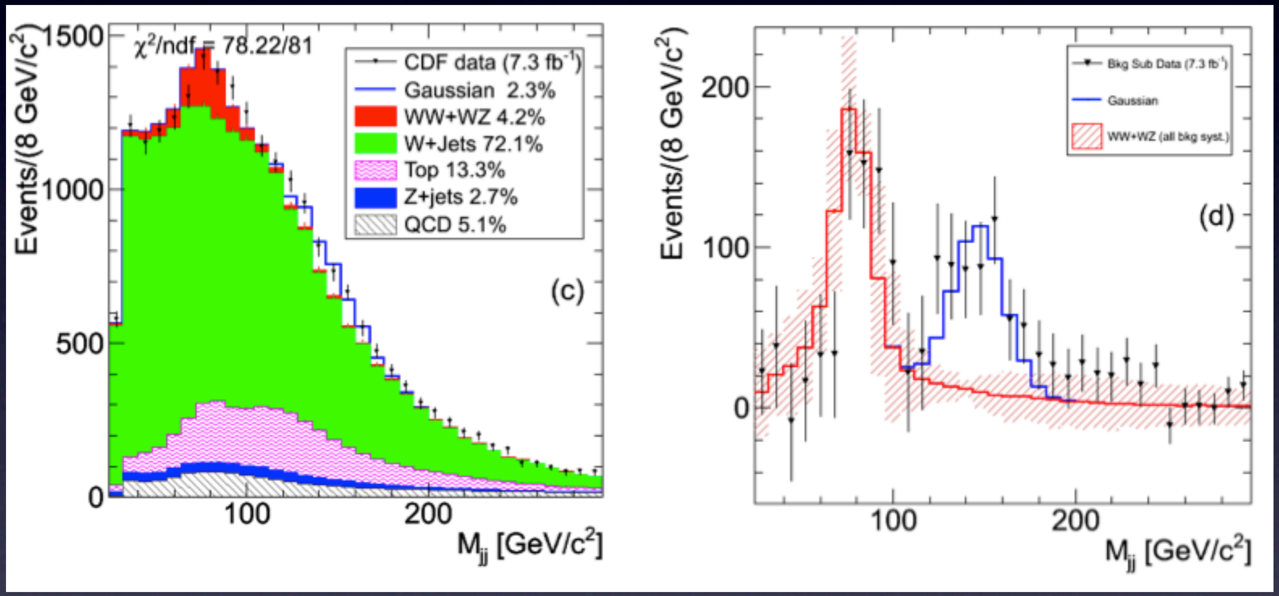
- a large numbers of tentative BSM explanations [ ... ]

# Meanwhile in Batavia

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

CDF col. 1104.0699

Update to include 7.3fb$^{-1}$ $\Rightarrow$ 4.1 $\sigma$




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

Since then

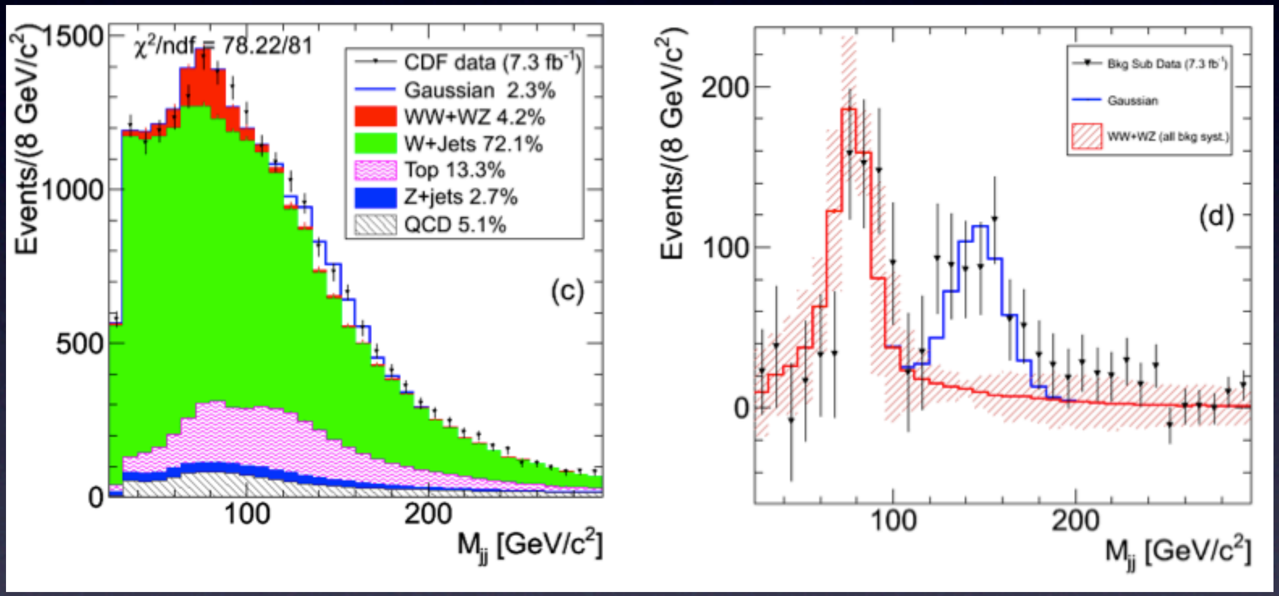
- a large numbers of tentative BSM explanations [ ... ]
- three SM analysis Plehn et al. 1104.4087; Sullivan & Menon 1104.3790; Campbell et al. 1105.4594

# Meanwhile in Batavia

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

CDF col. 1104.0699

Update to include 7.3fb$^{-1}$ $\Rightarrow$ 4.1 $\sigma$




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

Since then

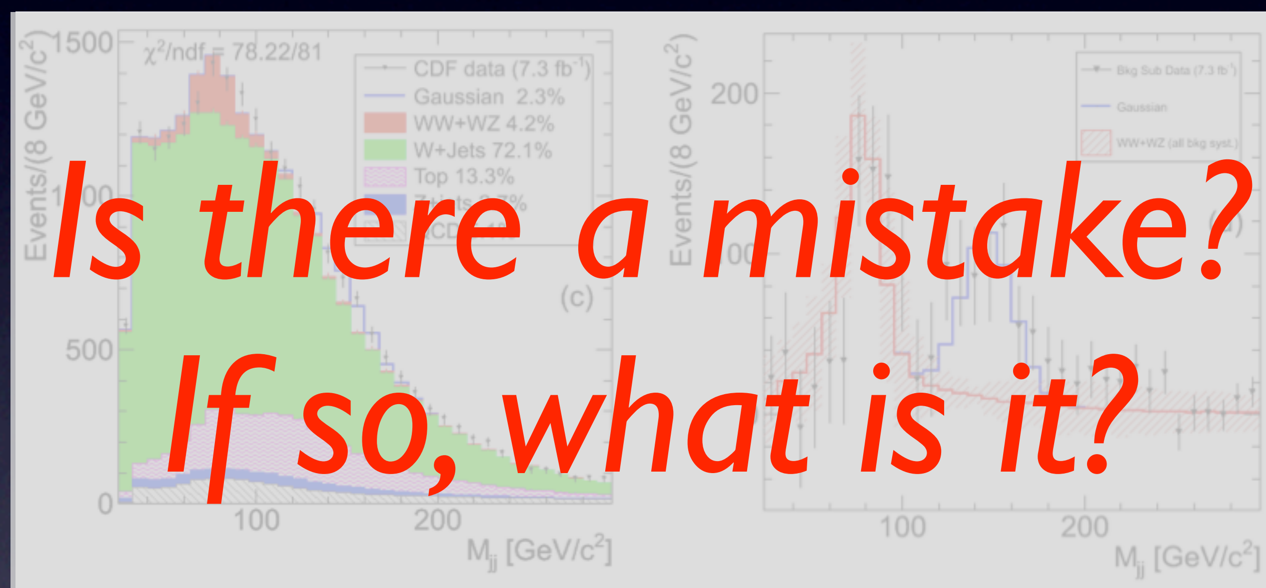
- a large numbers of tentative BSM explanations [ ... ]
- three SM analysis Plehn et al. 1104.4087; Sullivan & Menon 1104.3790; Campbell et al. 1105.4594
- D0 data do *not* support excess seen by CDF D0 col. 1106.1921

# Meanwhile in Batavia

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

CDF col. 1104.0699

Update to include $7.3 fb^{-1}$ ⇒ 4.1 σ




*Is there a mistake?*

*If so, what is it?*

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

Other current few σ:

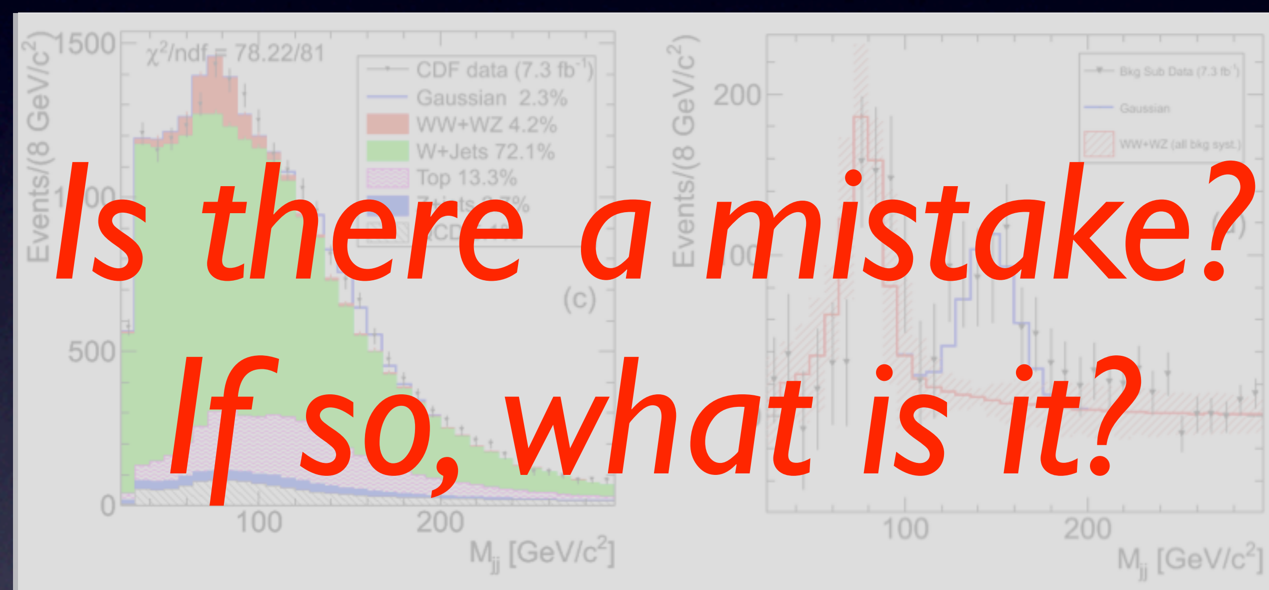
$B_s \to \mu^+\mu^-$ [CDF], dimuon charge asymmetry [D0], W+b [CDF], tt asymmetry [CDF, D0], $(g-2)_\mu$, CP violation in $D^0$ decays [LHCb] . . .

# Meanwhile in Batavia

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

CDF col. 1104.0699

Update to include 7.3fb$^{-1}$ $\Rightarrow$ 4.1 $\sigma$




***Is there a mistake?***

***If so, what is it?***

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

Other current few $\sigma$:

$B_s \rightarrow \mu^+\mu^-$ [CDF], dimuon charge asymmetry [D0], W+b [CDF], tt asymmetry [CDF, D0], $(g-2)_\mu$, CP violation in $D^0$ decays [LHCb] . . .

At the LHC expect many similar cases

- need confirmation by independent experimental group
- best possible SM predictions and solid BSM predictions very helpful

# Toolkit

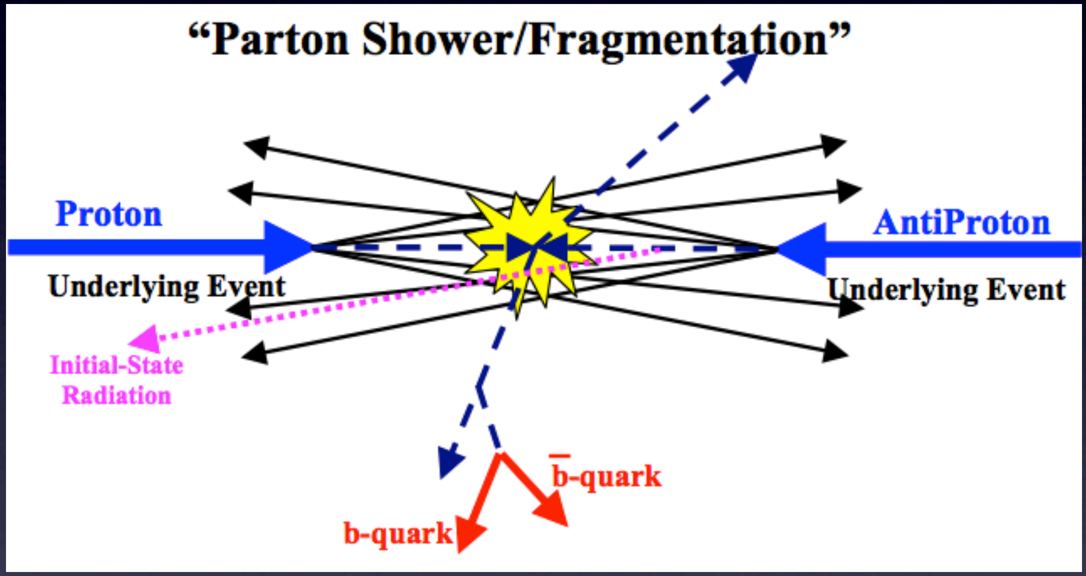
- Parton shower (PS) [e.g. Pythia, Herwig, Ariadne, ... ]
- Matrix elements (ME) generators, usually + PS [e.g. Alpgen, Helac, Madgraph, Sherpa ... ]
- NLO [BlackHat, Cuttools, GoSam, Helac-NLO, MCFM, NLOjet++, Rocket, Topaz, Rocket, VecBos, VBF@NLO ... ]
- NLO+ PS [(a)MC@NLO and POWHEG]
- NLO + NLL (NNLL) analy. resummations [CAESAR, ResBos]
- NLO QCD+EW [Hawk, Horace, iHixs, Photos, RGHiggs, Winhac, WZGRAD2, ... ]
- approx. NNLO [e.g. Hathor ... ]
- inclusive NNLO [e.g. iHixs, VH@NNLO ... ]
- exclusive NNLO with flexible cuts [FEHIP, H@NNLO, FEWZ, DY@NNLO]
- NNLO + NNLL analy. resummations [e.g. thrust in $e^+e^- \rightarrow$ 3jets ... ]
- ...

increasing difficulty with loops or legs
available for lower multiplicities

# Monte Carlos


Essentially every LHC analysis will make use of one or more Monte Carlo (MC) simulations 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 sophisticated study uses "just Pythia/Herwig". To describe hard QCD radiation need, at least, exact matrix elements (ME), such as Alpgen, Madgraph, Sherpa, ...

# Progress in PS/ME

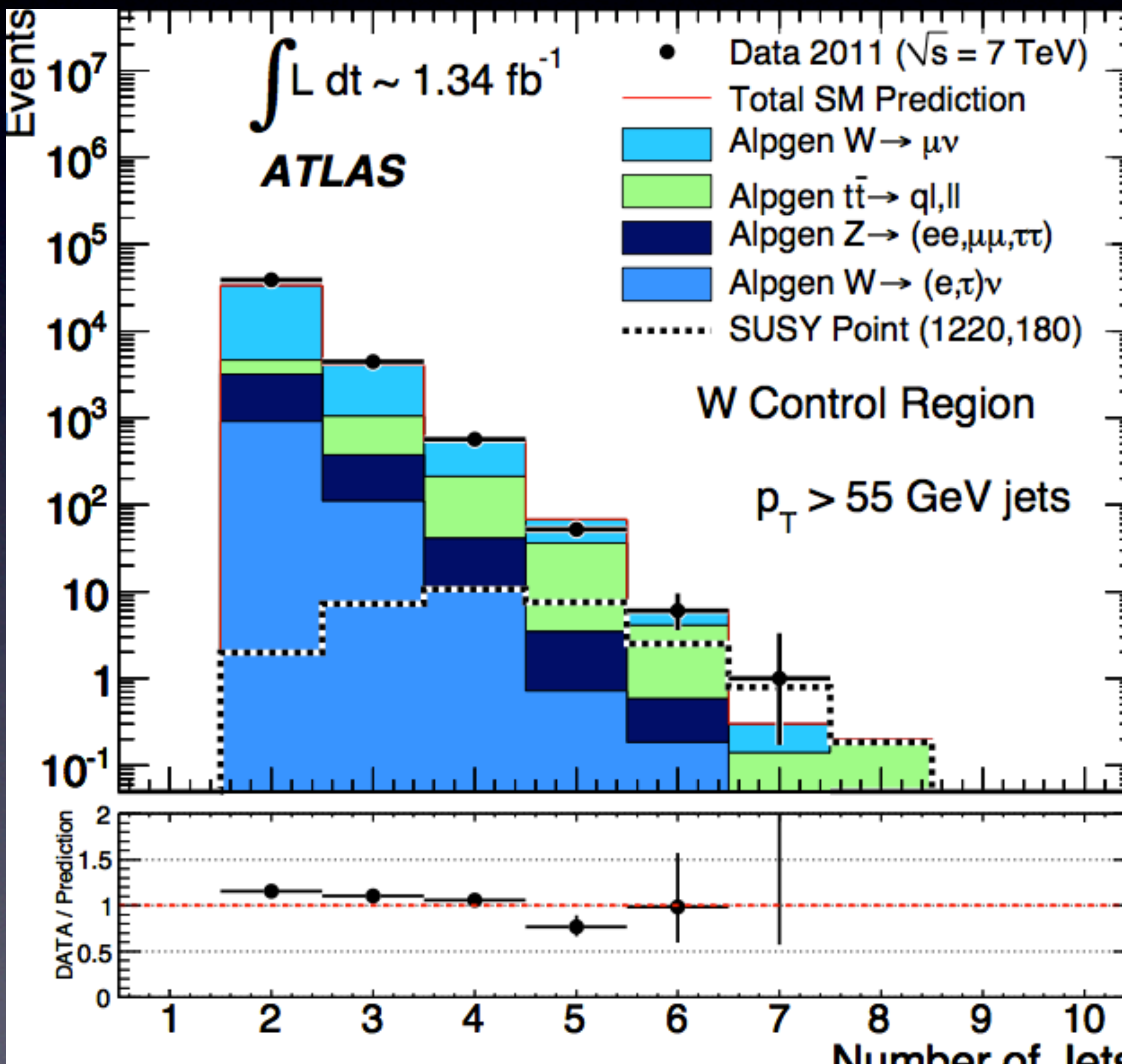
- Pythia (8.1): new $p_t$-ordered shower + sophisticated MPI, possibility to select two hard interactions in the same event, several new processes in and beyond at SM
- Herwig++ (2.4): updated angular-ordered shower, default includes now multiple interaction model, additional models of BSM
- Sherpa (1.3): dipole shower, improved integration routines, efficient multi-leg ME (Comix) via CKKW matching
- Madgraph (5.0): completely new diagram generation algorithm, efficient decay-chain package, automated HELAS routines, more extended spin and color support, increased speed and stability, . . .

# Progress in PS/ME

- Pythia (8.1): new $p_t$-ordered shower + sophisticated MPI, possibility to select two hard interactions in the same event, several new processes in and beyond at SM
- Herwig++ (2.4): updated angular-ordered shower, default includes now multiple interaction model, additional models of BSM
- Sherpa (1.3): dipole shower, improved integration routines, efficient multi-leg ME (Comix) via CKKW matching
- Madgraph (5.0): completely new diagram generation algorithm, efficient decay-chain package, automated HELAS routines, more extended spin and color support, increased speed and stability, . . .

Fast progress in various directions
These codes will undergo continuous stress test in the coming years.
*How are they doing right now?*

# One (impressive) example

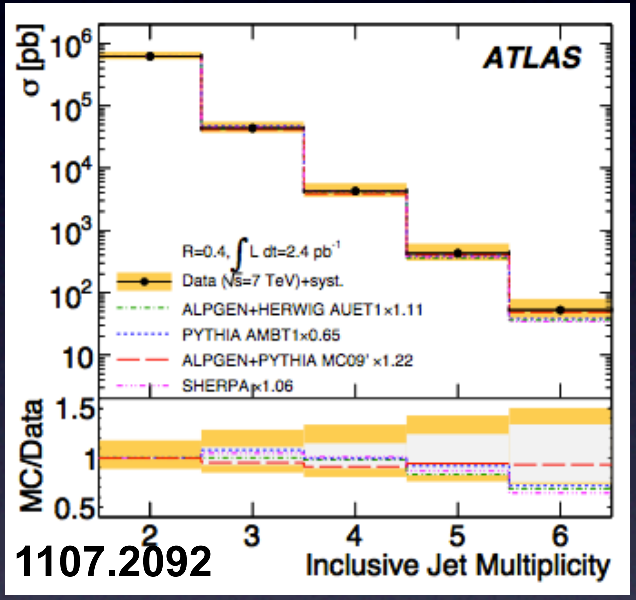



Once the normalization is fixed in the low multiplicity bin, the agreement at high multiplicity is spectacular

Plot taken from ATLAS col. 1110.2299
uses
Alpgen Mangano et al. hep-ph/0206293
[1000+ this month]

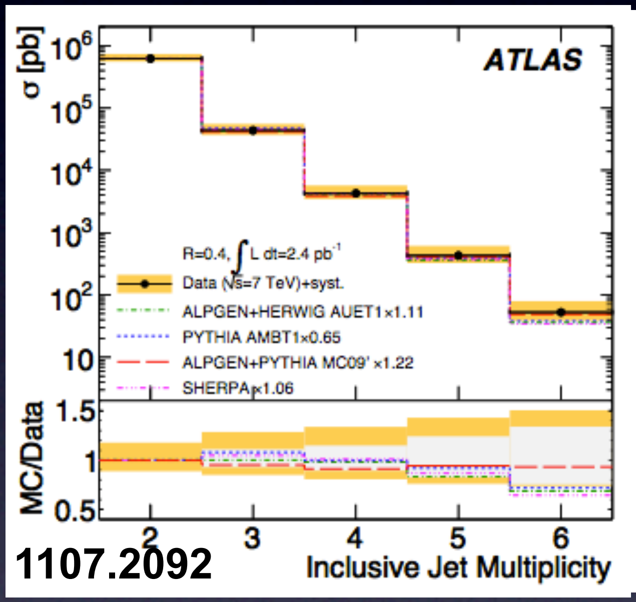
# PS/ME at LHC

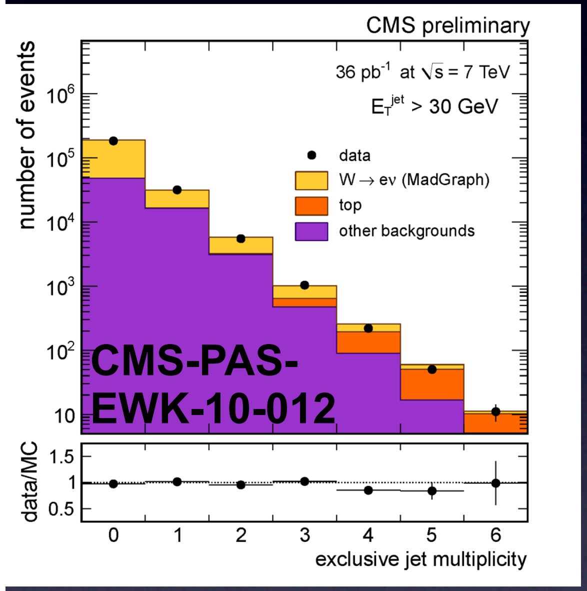
*In terms of describing first LHC data, it is surprising how well these tools work even without particular tunings (but of course the devil is in the ~20% details . . . )*



# PS/ME at LHC

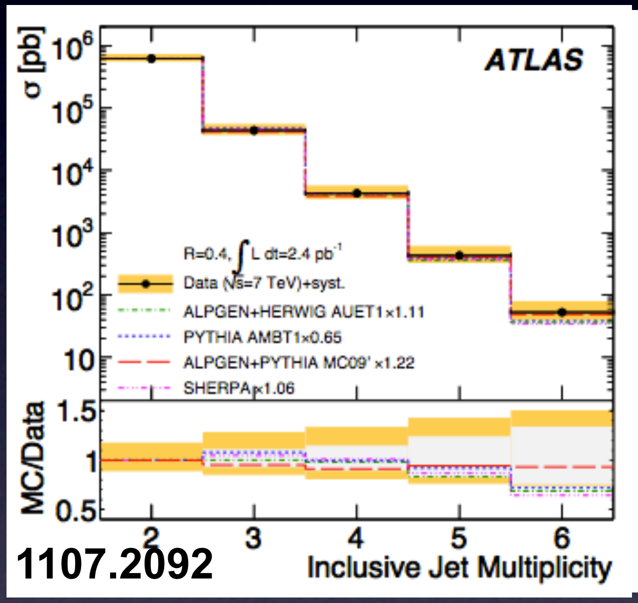
*In terms of describing first LHC data, it is surprising how well these tools work even without particular tunings (but of course the devil is in the ~20% details . . . )*

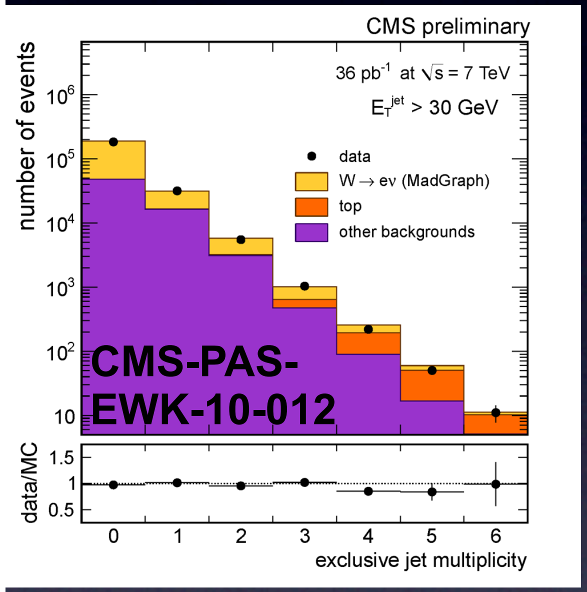


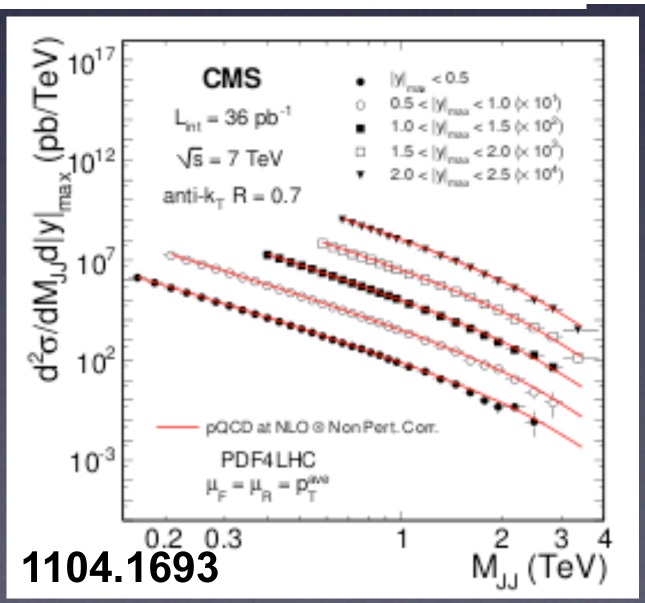



# PS/ME at LHC

*In terms of describing first LHC data, it is surprising how well these tools work even without particular tunings (but of course the devil is in the ~20% details . . . )*

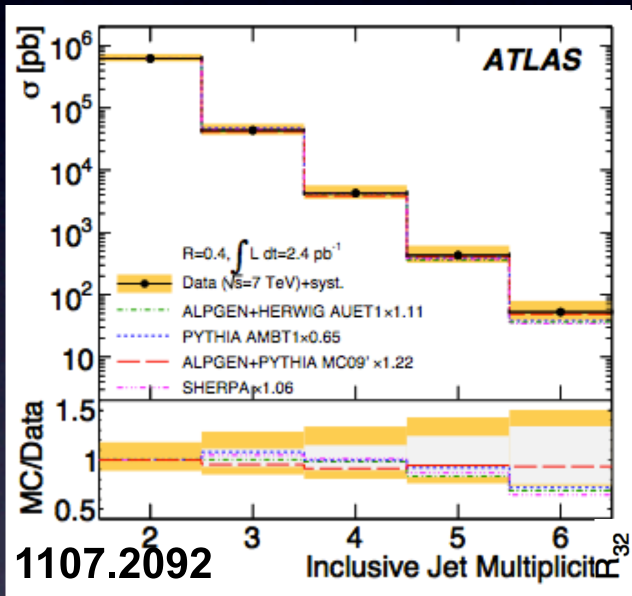


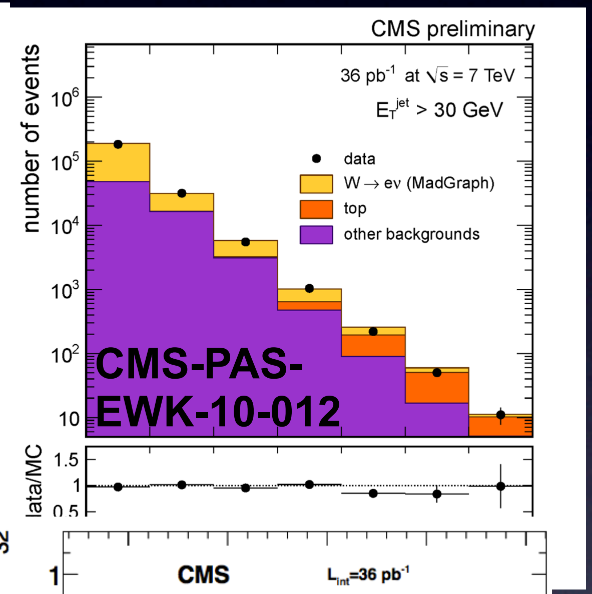



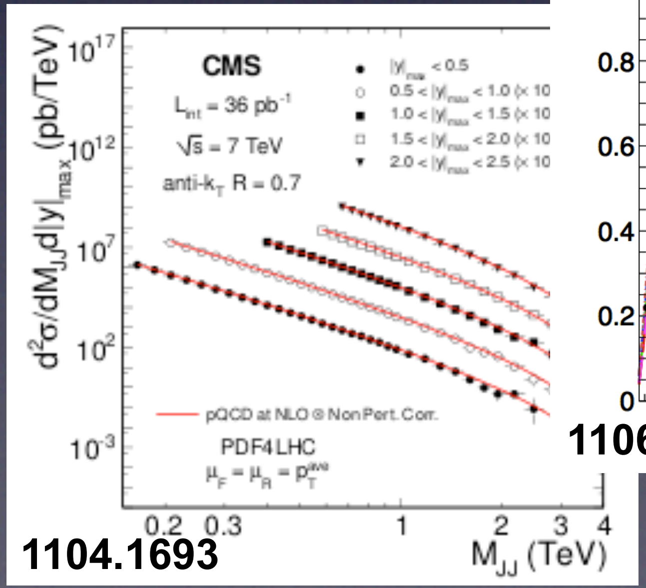



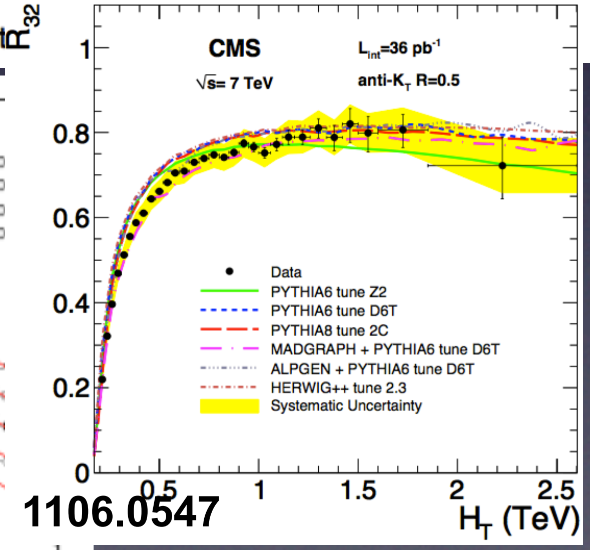
# PS/ME at LHC

*In terms of describing first LHC data, it is surprising how well these tools work even without particular tunings (but of course the devil is in the ~20% details . . . )*



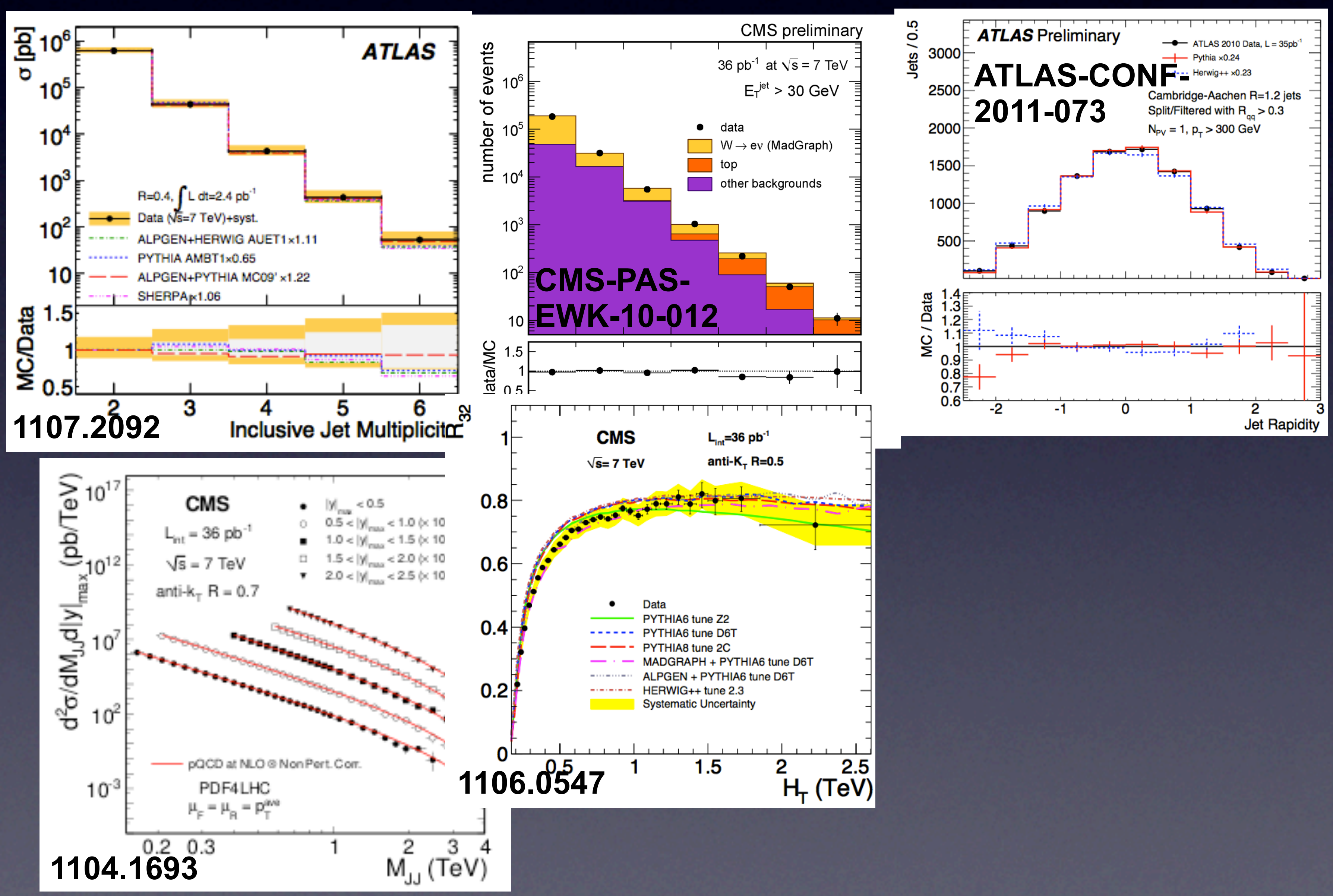



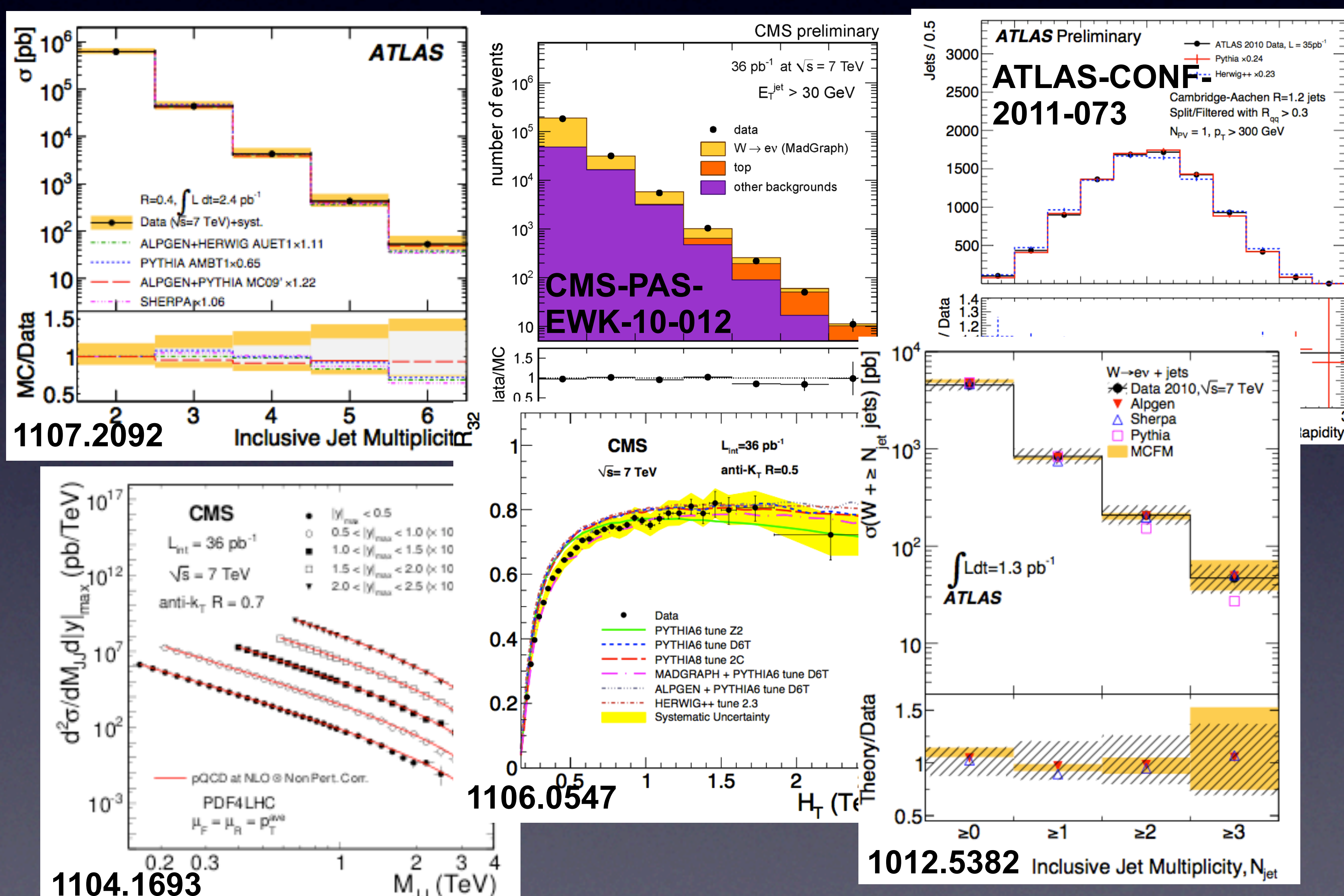
# PS/ME at LHC

*In terms of describing first LHC data, it is surprising how well these tools work even without particular tunings (but of course the devil is in the ~20% details . . . )*



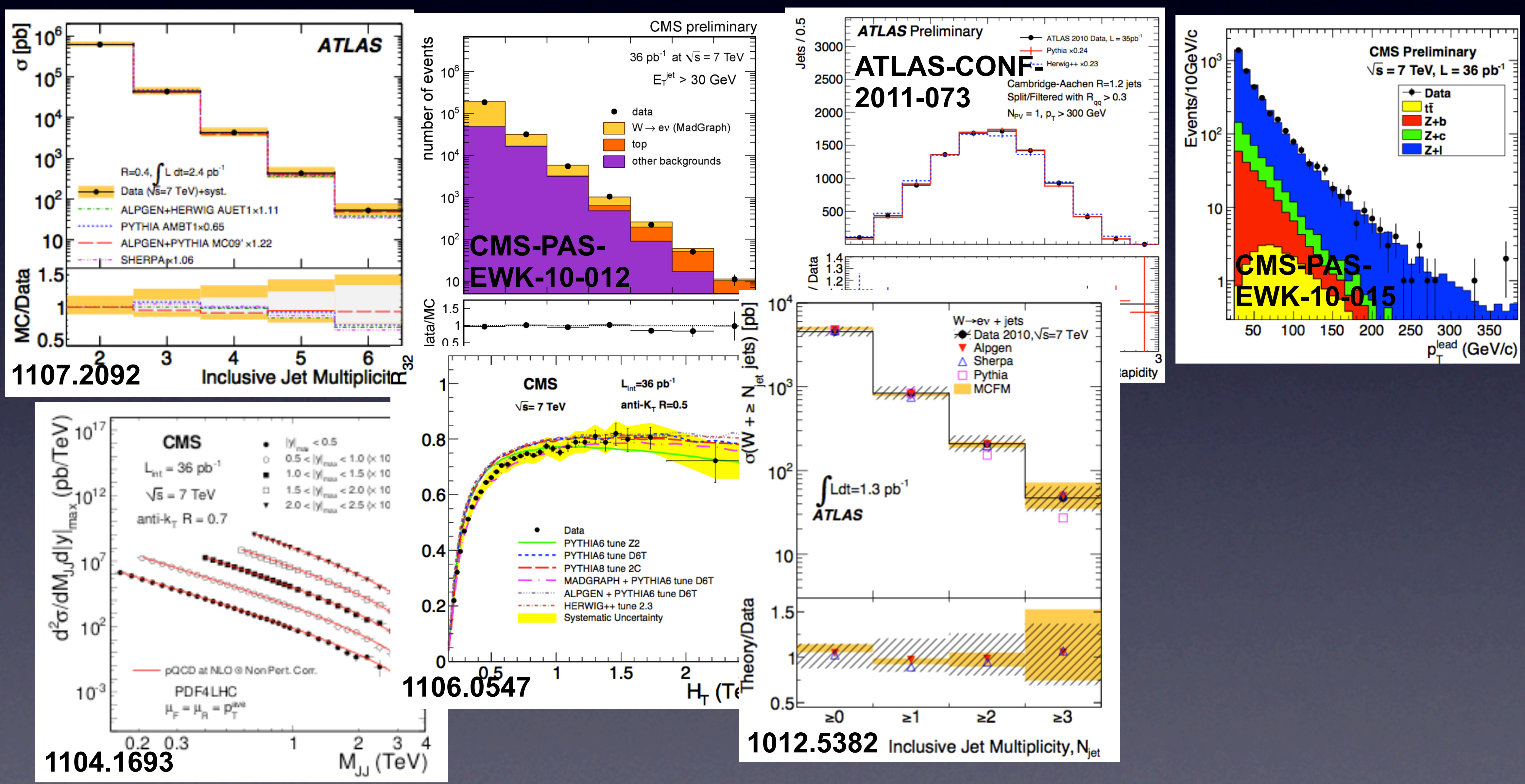
# PS/ME at LHC

*In terms of describing first LHC data, it is surprising how well these tools work even without particular tunings (but of course the devil is in the ~20% details . . . )*



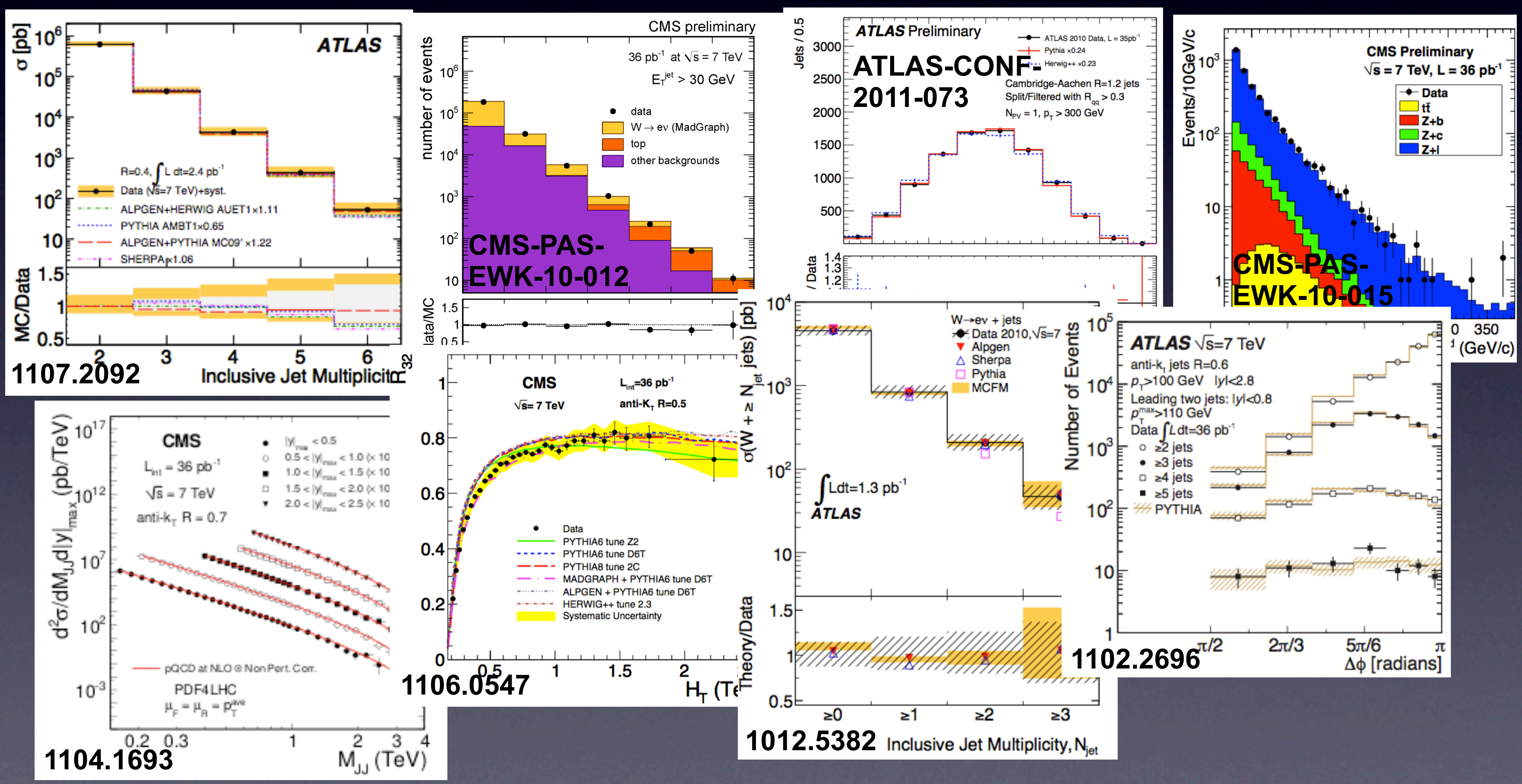
# PS/ME at LHC

*In terms of describing first LHC data, it is surprising how well these tools work even without particular tunings (but of course the devil is in the ~20% details ... )*



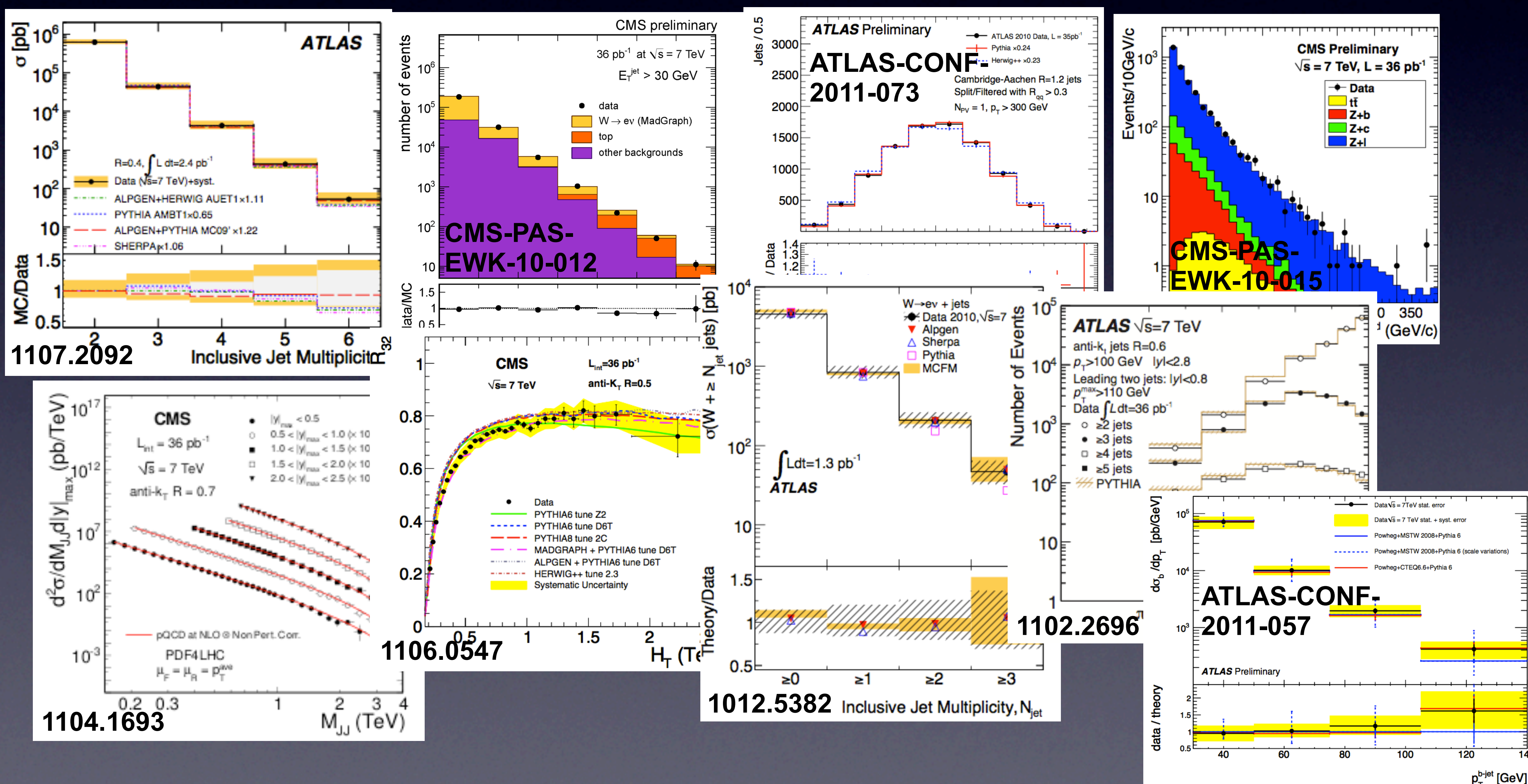
# PS/ME at LHC

*In terms of describing first LHC data, it is surprising how well these tools work even without particular tunings (but of course the devil is in the ~20% details . . . )*



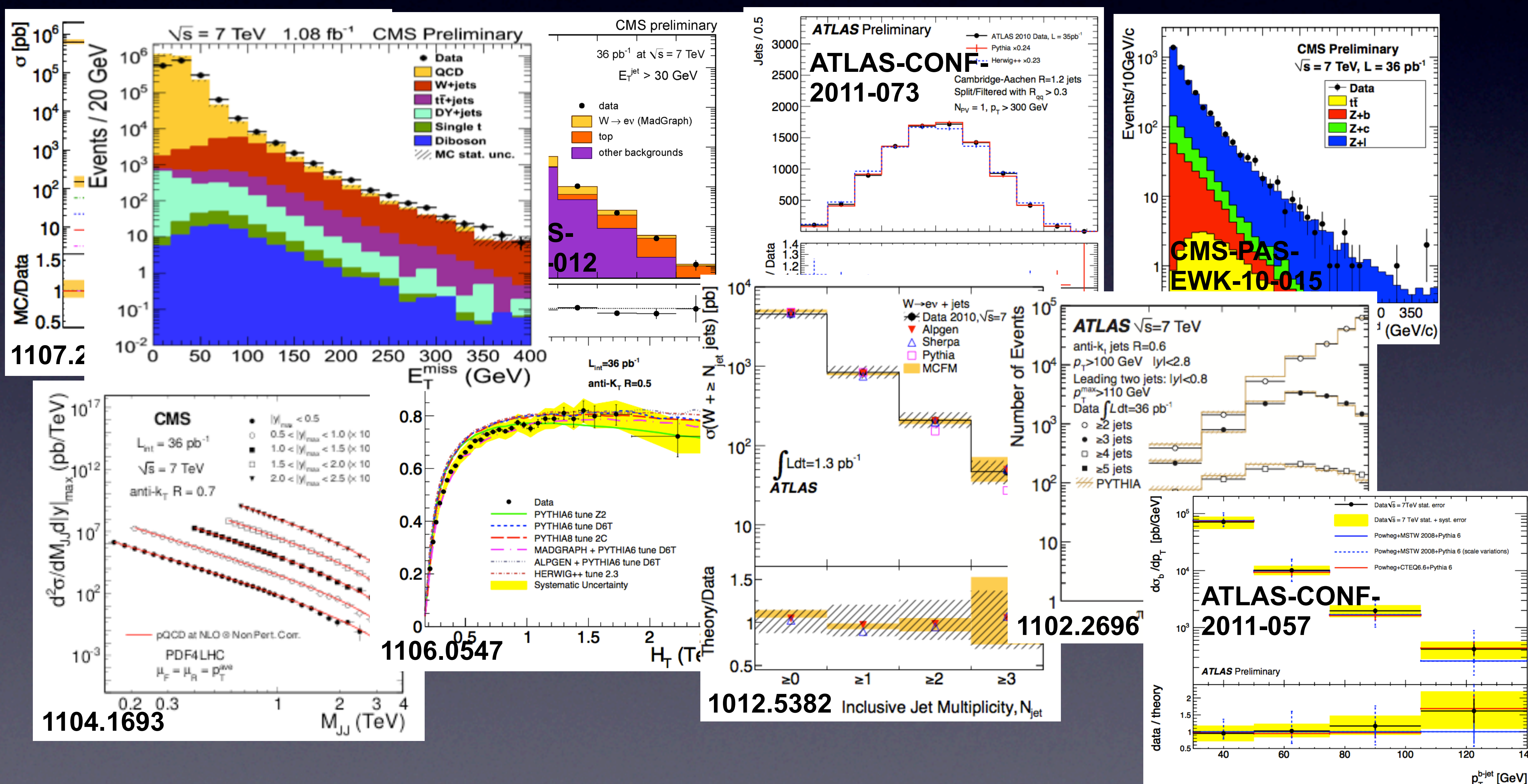
# PS/ME at LHC

*In terms of describing first LHC data, it is surprising how well these tools work even without particular tunings (but of course the devil is in the ~20% details . . . )*



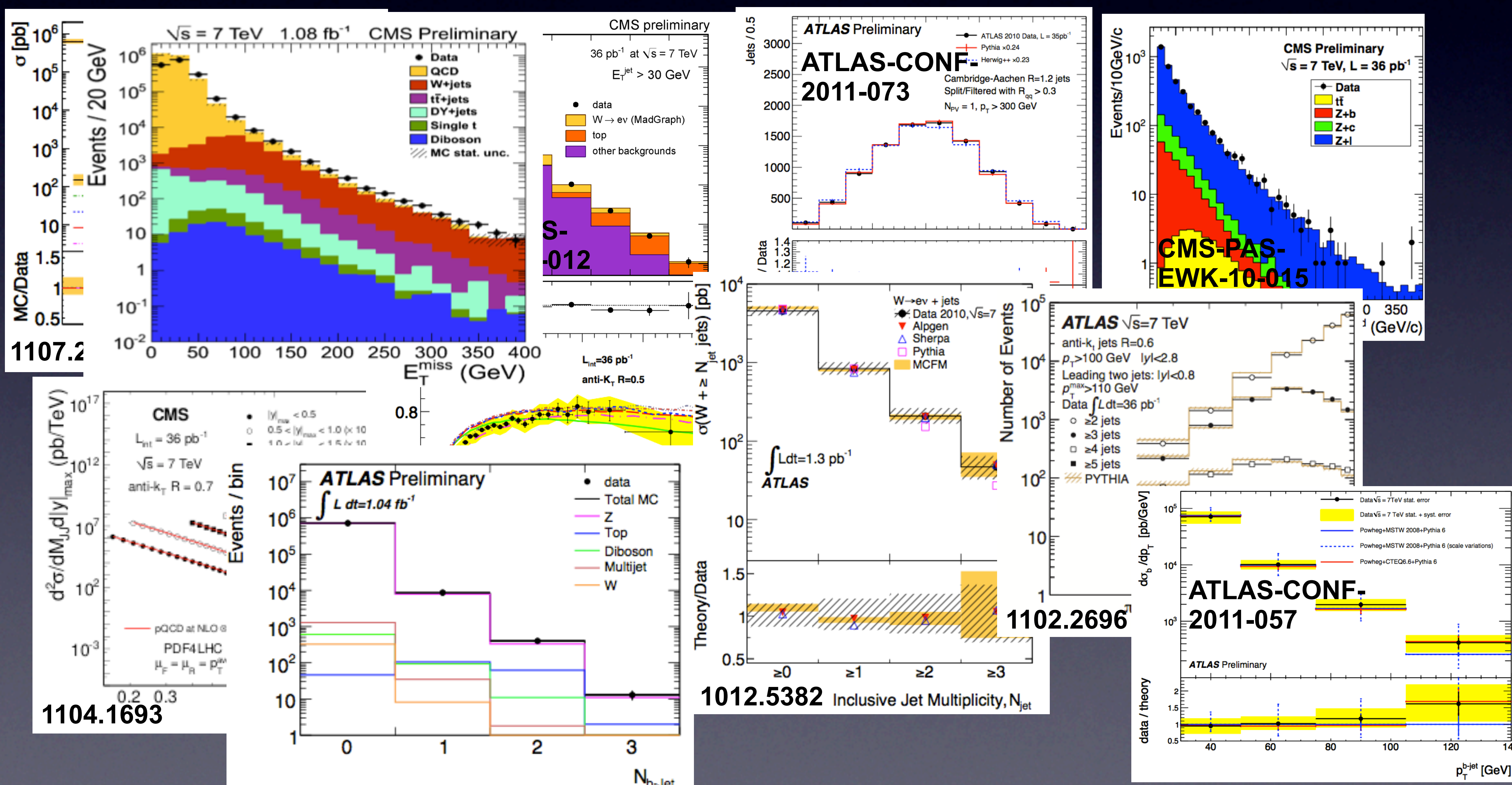
# PS/ME at LHC

*In terms of describing first LHC data, it is surprising how well these tools work even without particular tunings (but of course the devil is in the ~20% details . . . )*



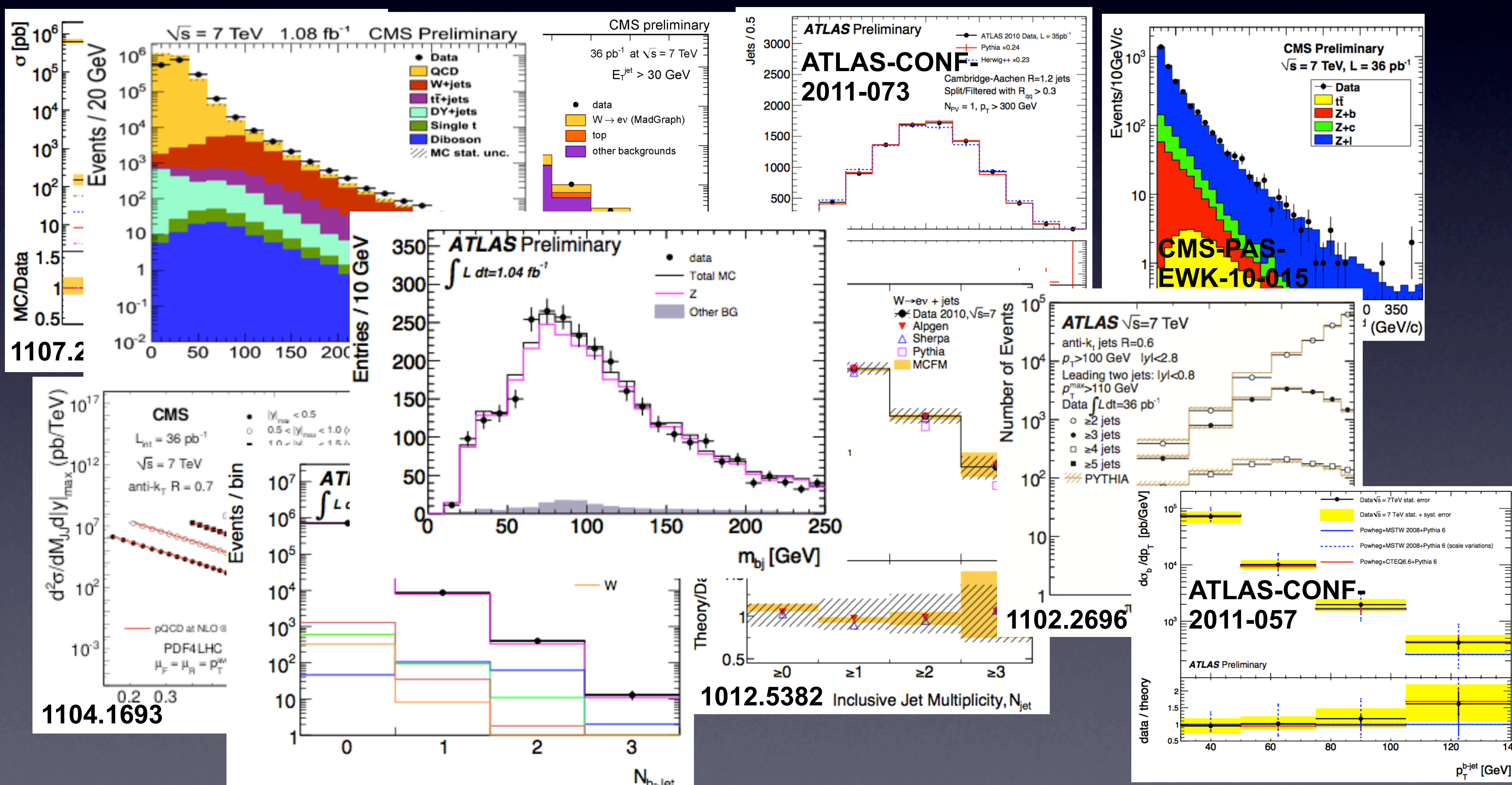
# PS/ME at LHC

*In terms of describing first LHC data, it is surprising how well these tools work even without particular tunings (but of course the devil is in the ~20% details . . . )*



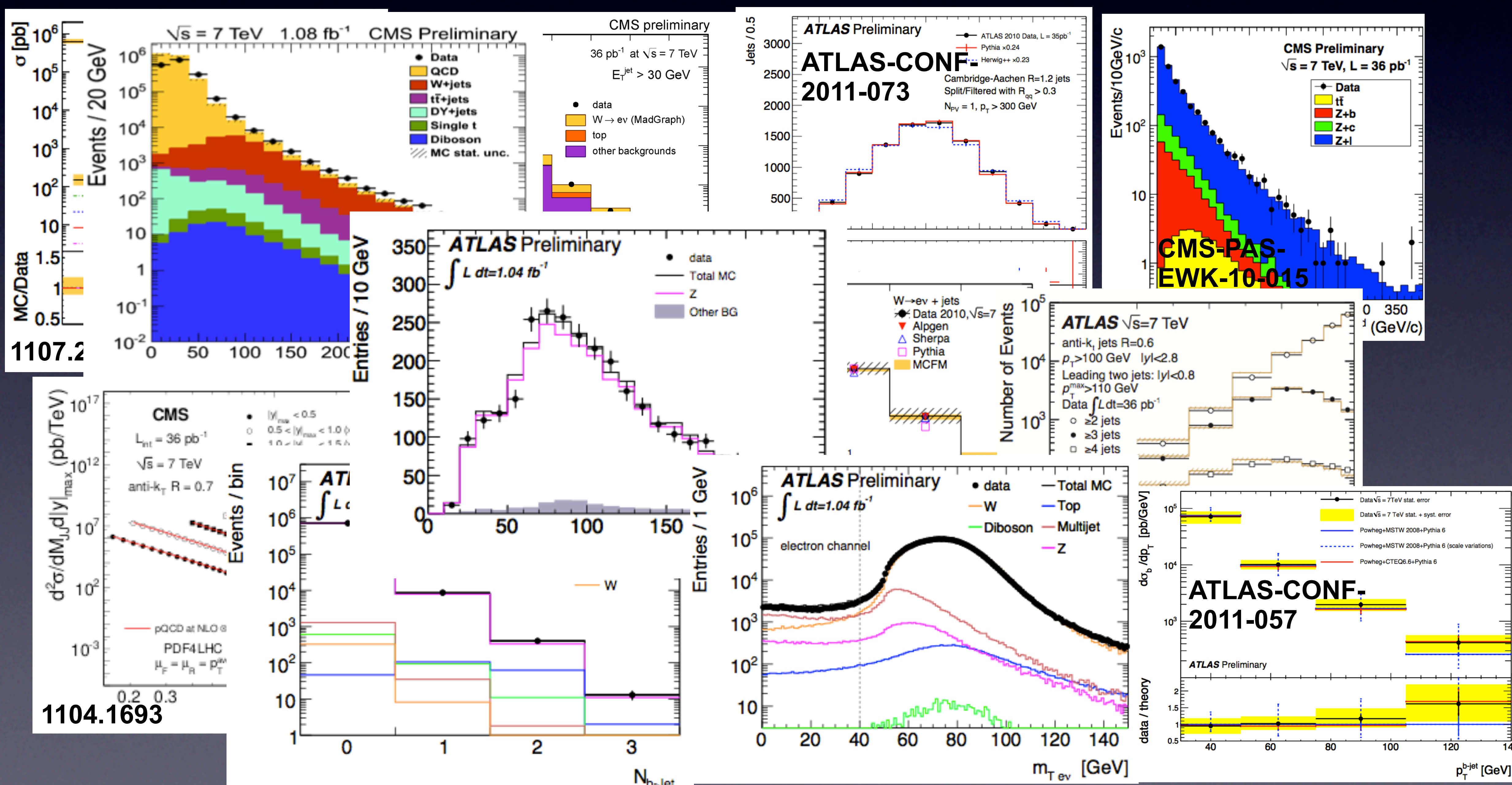
# PS/ME at LHC

*In terms of describing first LHC data, it is surprising how well these tools work even without particular tunings (but of course the devil is in the ~20% details . . . )*



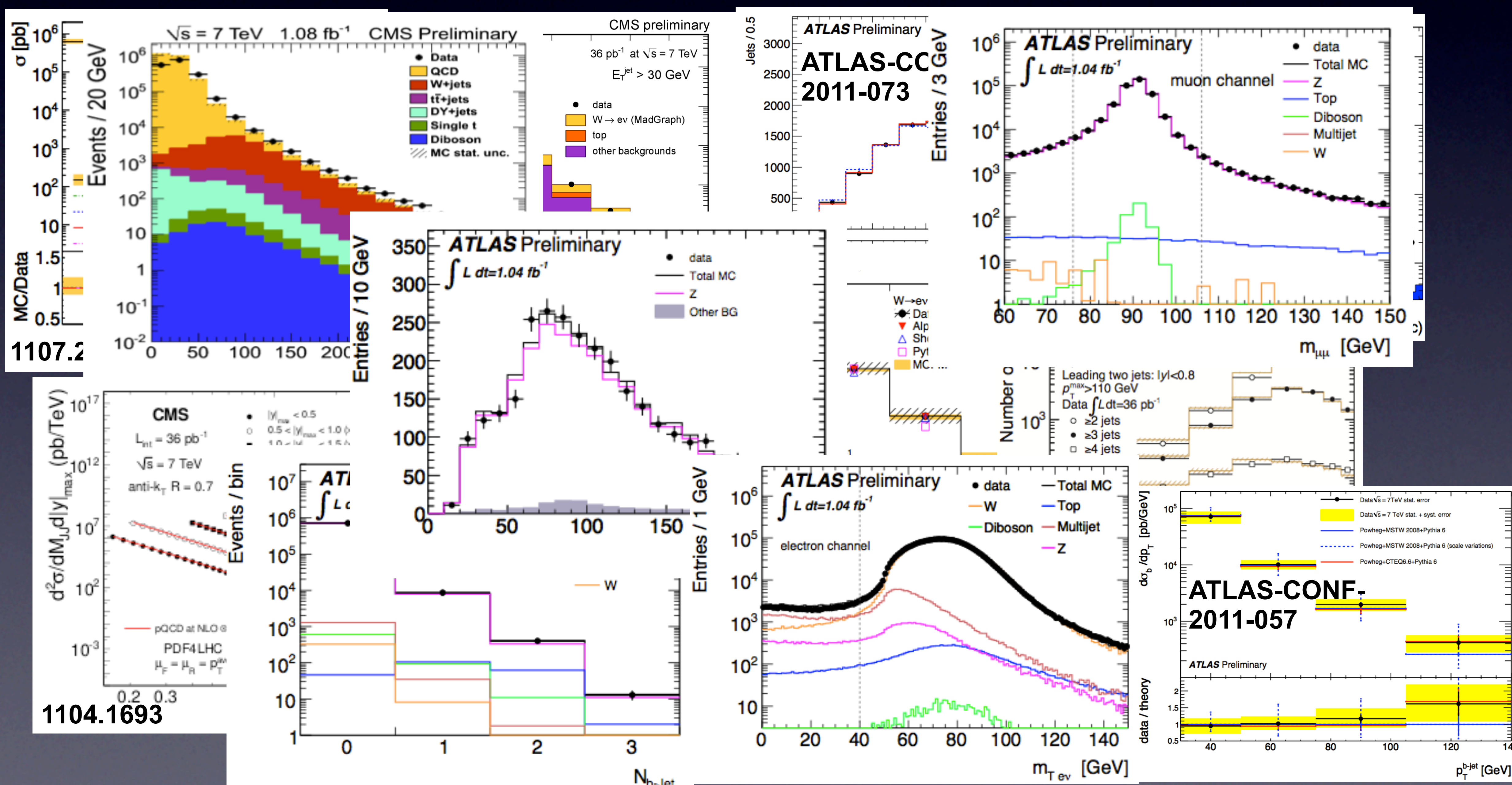
# PS/ME at LHC

*In terms of describing first LHC data, it is surprising how well these tools work even without particular tunings (but of course the devil is in the ~20% details . . . )*



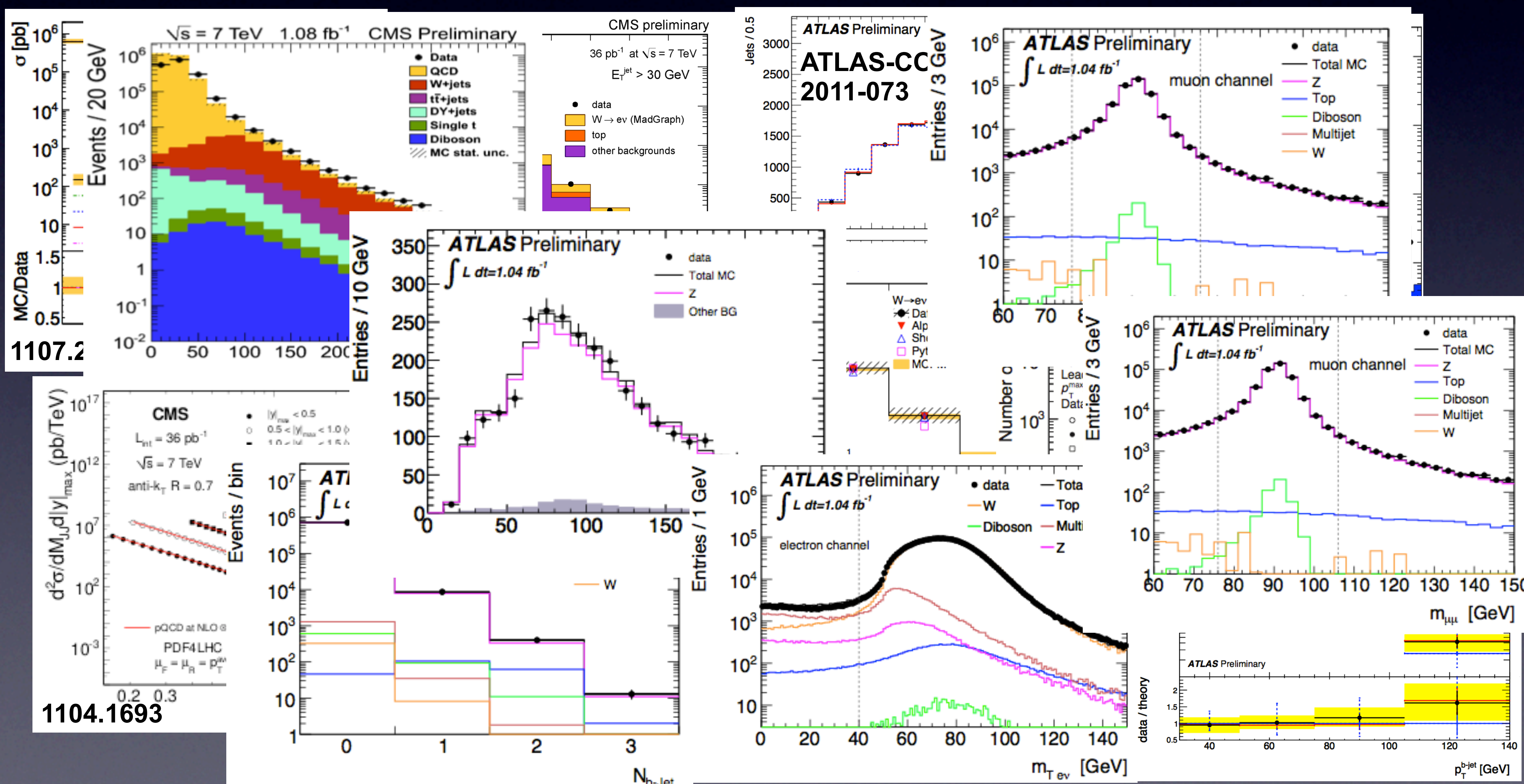
# PS/ME at LHC

*In terms of describing first LHC data, it is surprising how well these tools work even without particular tunings (but of course the devil is in the ~20% details . . . )*



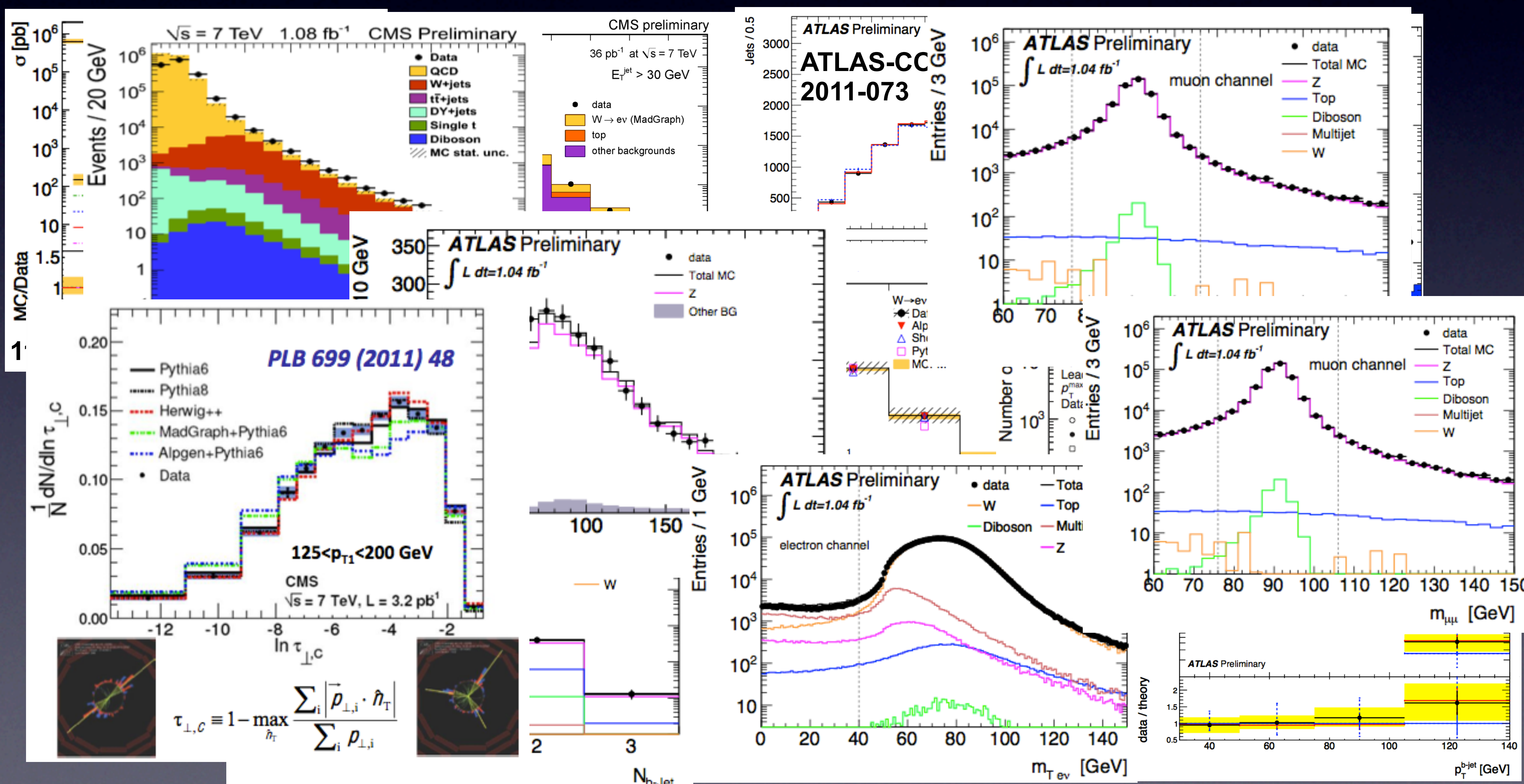
# PS/ME at LHC

*In terms of describing first LHC data, it is surprising how well these tools work even without particular tunings (but of course the devil is in the ~20% details . . . )*



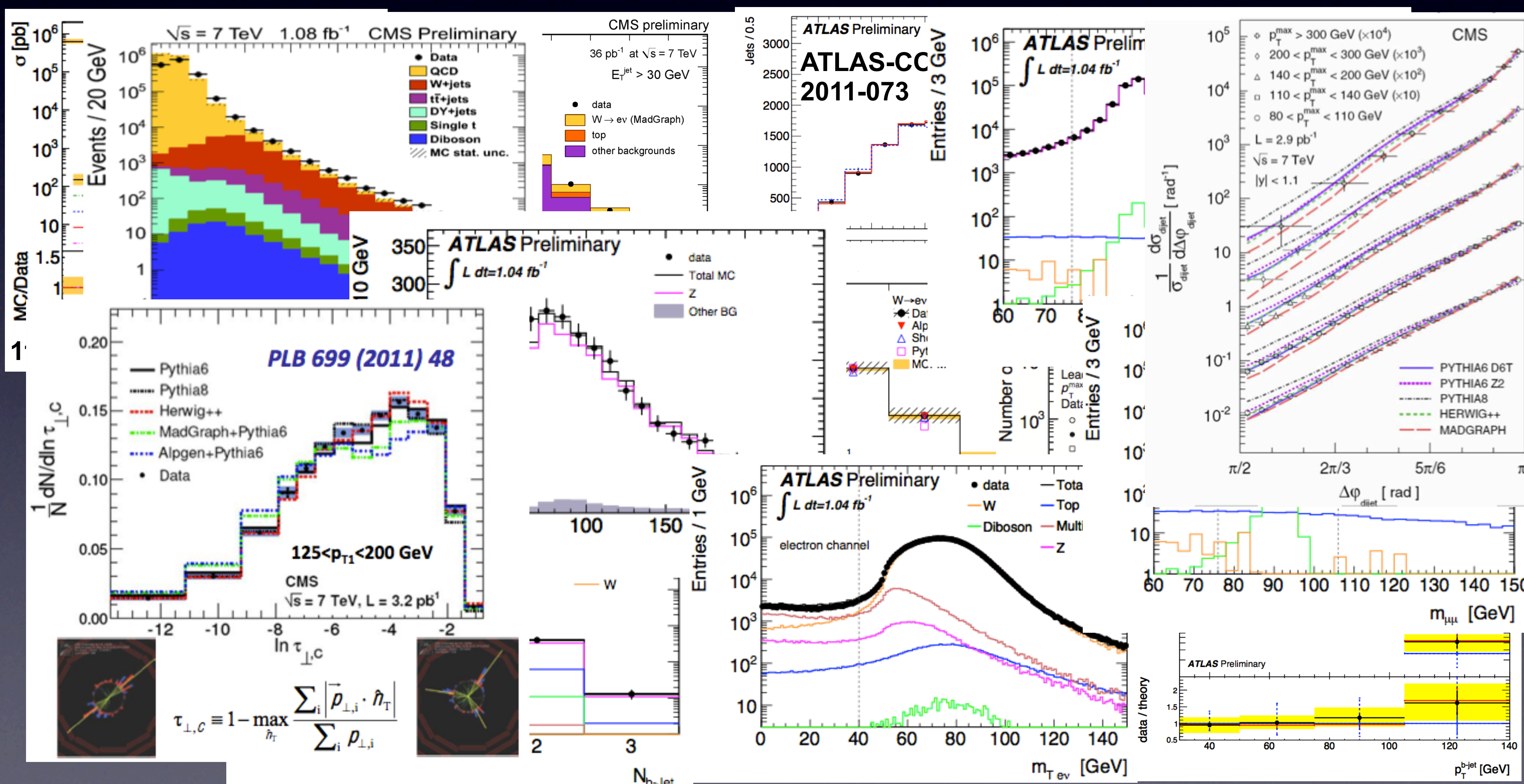
# PS/ME at LHC

*In terms of describing first LHC data, it is surprising how well these tools work even without particular tunings (but of course the devil is in the ~20% details . . . )*



# PS/ME at LHC

*In terms of describing first LHC data, it is surprising how well these tools work even without particular tunings (but of course the devil is in the ~20% details . . . )*



# The NLO revolution

Theorists like to advertise NLO using the reduction of scale (theory) uncertainty as an argument. However, the strongest argument in support of NLO is its past success in describing LEP and Tevatron data

I'll spare you here one more slide full of plots ...

# The NLO revolution

Theorists like to advertise NLO using the reduction of scale (theory) uncertainty as an argument. However, the strongest argument in support of NLO is its past success in describing LEP and Tevatron data

I'll spare you here one more slide full of plots ...

An industrial effort to compute NLO multi-leg processes

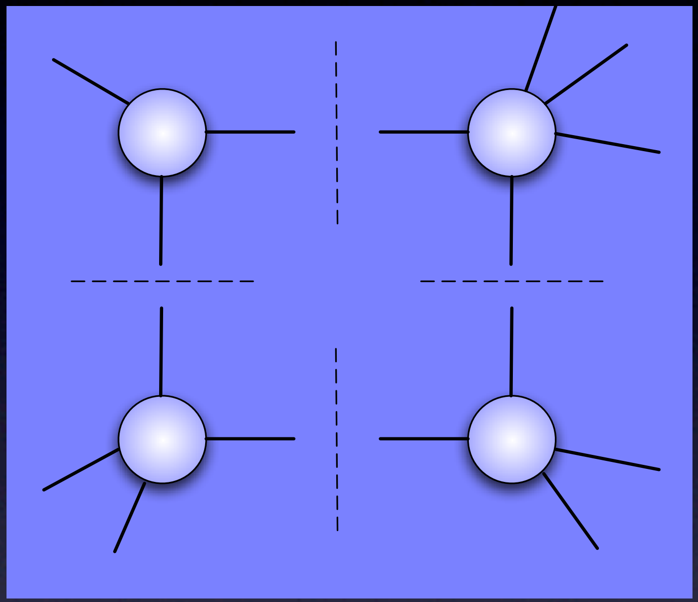
Anastasiou, Andersen, Badger, Becker, Bevilacqua, Bredenstein, Berger, Bern, Binoth, Britto, Cachazo, Campbell, Caola, Cullen, Czakon, Dawson, Denner, Diana, Dittmaier, Dixon, Draggiotis, Ellis, Febres-Cordero, Feng, Forde, Giele, Gleisberg, Greiner, Guffanti, Guillet, van Hameren, Heinrich, Hoeche, Kallweit, Kleinschmidt, Karg, Kauer, Kosower, Kunszt, Ita, Jaeger, Lazopoulos, Maitre, Mastrolia, Melia, Melnikov, Oleari, Ossola, Ozeren, Pilon, Pittau, Papadopoulos, Pozzorini, Reiter, Reuschle, Reuter, Rodgers, Rontsch, Sanguinetti, Schmacher, Schumann, Tramontano, Weinzierl, Winter, Worek, GZ, Zeppenfeld ...

# Breakthrough ideas

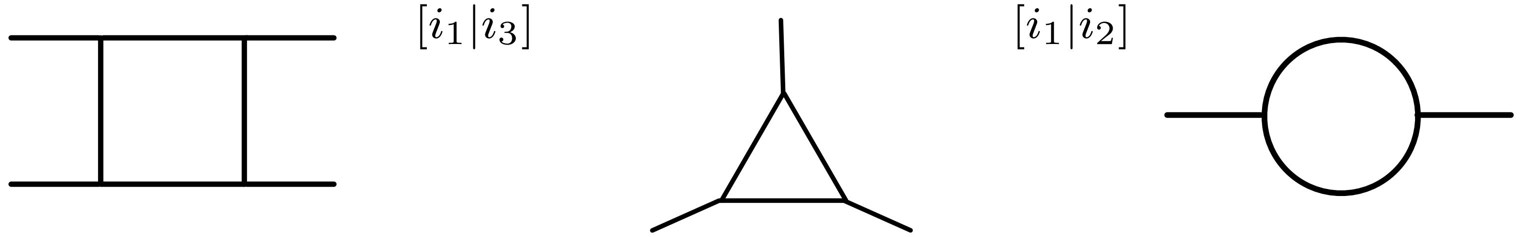
Aim: no Feynman diagrams (factorial divergence with the # of particles)

- sew together tree level amplitudes to compute loop amplitudes [on-shell states, cuts, unitarity ... ]

- OPP: extract coefficients of master integrals by evaluating the amplitude at specific values of the 4-D loop momentum [algebraic method]



$$\mathcal{A}_N = \sum_{[i_1|i_4]} \left( d_{i_1 i_2 i_3 i_4} \; I^{(D)}_{i_1 i_2 i_3 i_4} \right) + \sum_{[i_1|i_3]} \left( c_{i_1 i_2 i_3} \; I^{(D)}_{i_1 i_2 i_3} \right) + \sum_{[i_1|i_2]} \left( b_{i_1 i_2} \; I^{(D)}_{i_1 i_2} \right) + \mathcal{R}$$



- 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

# Recent NLO results

These and related ideas led in the last two years to a number of 2 → 4 calculations

[W/Z + 3jets, $W^+W^+$ + 2jets, $W^+W^-$ + 2jets, ee → 5jets ...]

Berger, Bern, Dixon, Febres-Cordero, Forde, Gleisberg, Ita, Kosower, Maitre
Ellis, Frixione, Frederix, Giele, Kunszt, Melia, Melnikov, Rontsch, GZ

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

[WW + bb, tt + 2jets, tt + bb, bbbb ... ]

Bredenstein, Denner, Dittmaier, Kallweit, Pozzorini
Binoth, Greiner, Guffanti, Guillet, Reiter, Reuter
Bevilacqua, Czakon, van Hameren, Papadopoulos, Pittau, Worek

# Recent NLO results

These and related ideas led in the last two years to a number of $2 \to 4$ calculations

[$W/Z$ + 3jets, $W^+W^+$ + 2jets, $W^+W^-$ + 2jets, ee $\to$ 5jets ...]

Berger, Bern, Dixon, Febres-Cordero, Forde, Gleisberg, Ita, Kosower, Maitre
Ellis, Frixione, Frederix, Giele, Kunszt, Melia, Melnikov, Rontsch, GZ

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

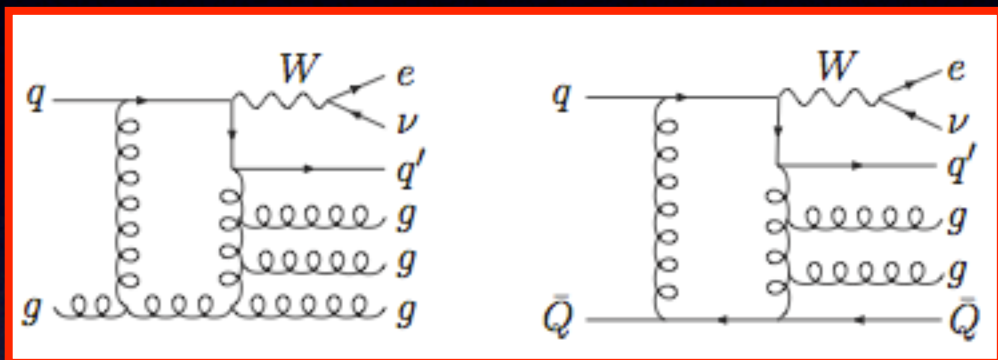
[WW + bb, tt + 2jets, tt + bb, bbbb ... ]

Bredenstein, Denner, Dittmaier, Kallweit, Pozzorini
Binoth, Greiner, Guffanti, Guillet, Reiter, Reuter
Bevilacqua, Czakon, van Hameren, Papadopoulos, Pittau, Worek

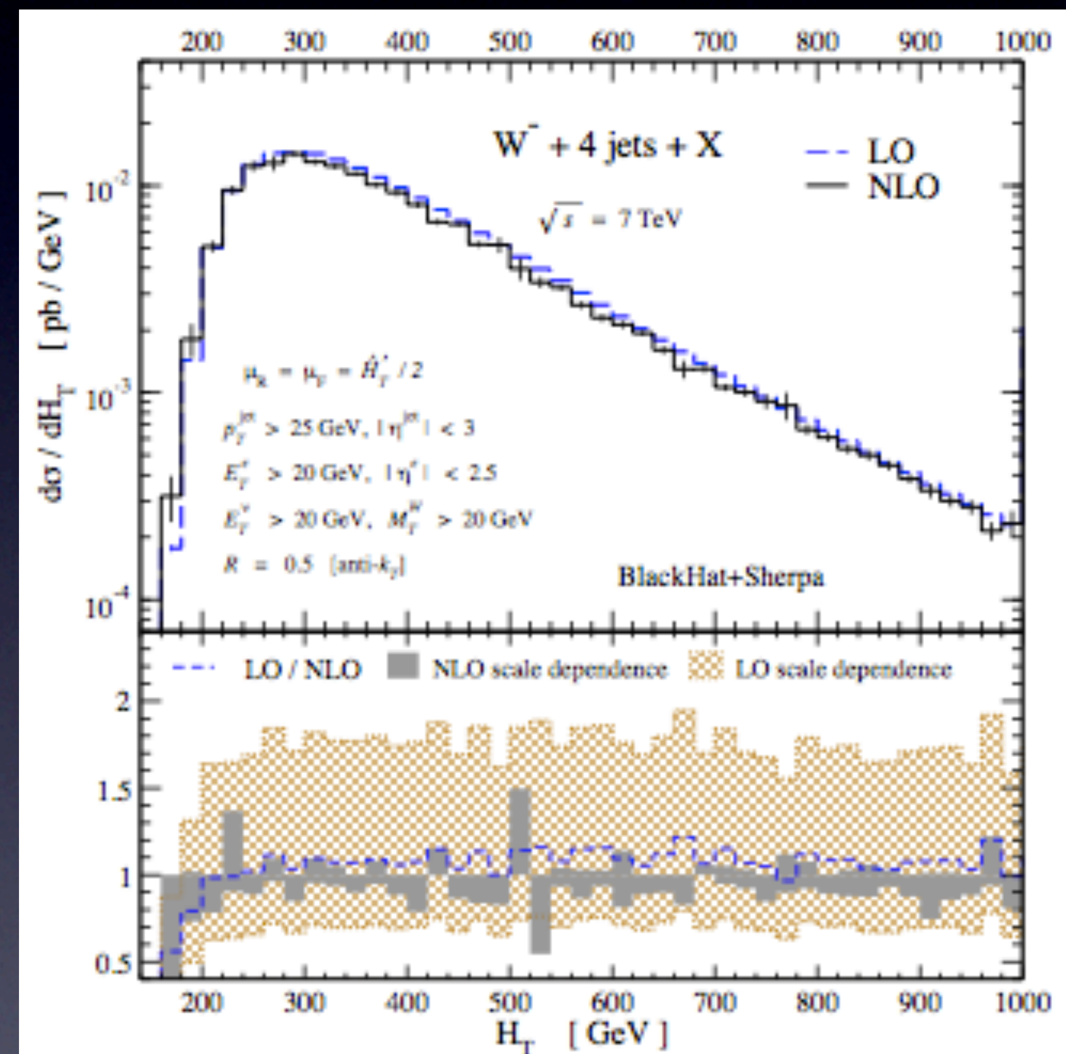
*The revolution is not in the applications that we see today, rather in the prospect for low-cost automated NLO calculations even beyond $2 \to 4$ in the near future*

# W + 4jets at NLO

Sample diagrams*




Berger et al. '10




- first pp → 5
- expected reduction of theoretical uncertainties
- key to top physics analyses: main background to tt in semi-leptonic channel
- Z + 4jets in progress (⇒ SUSY)

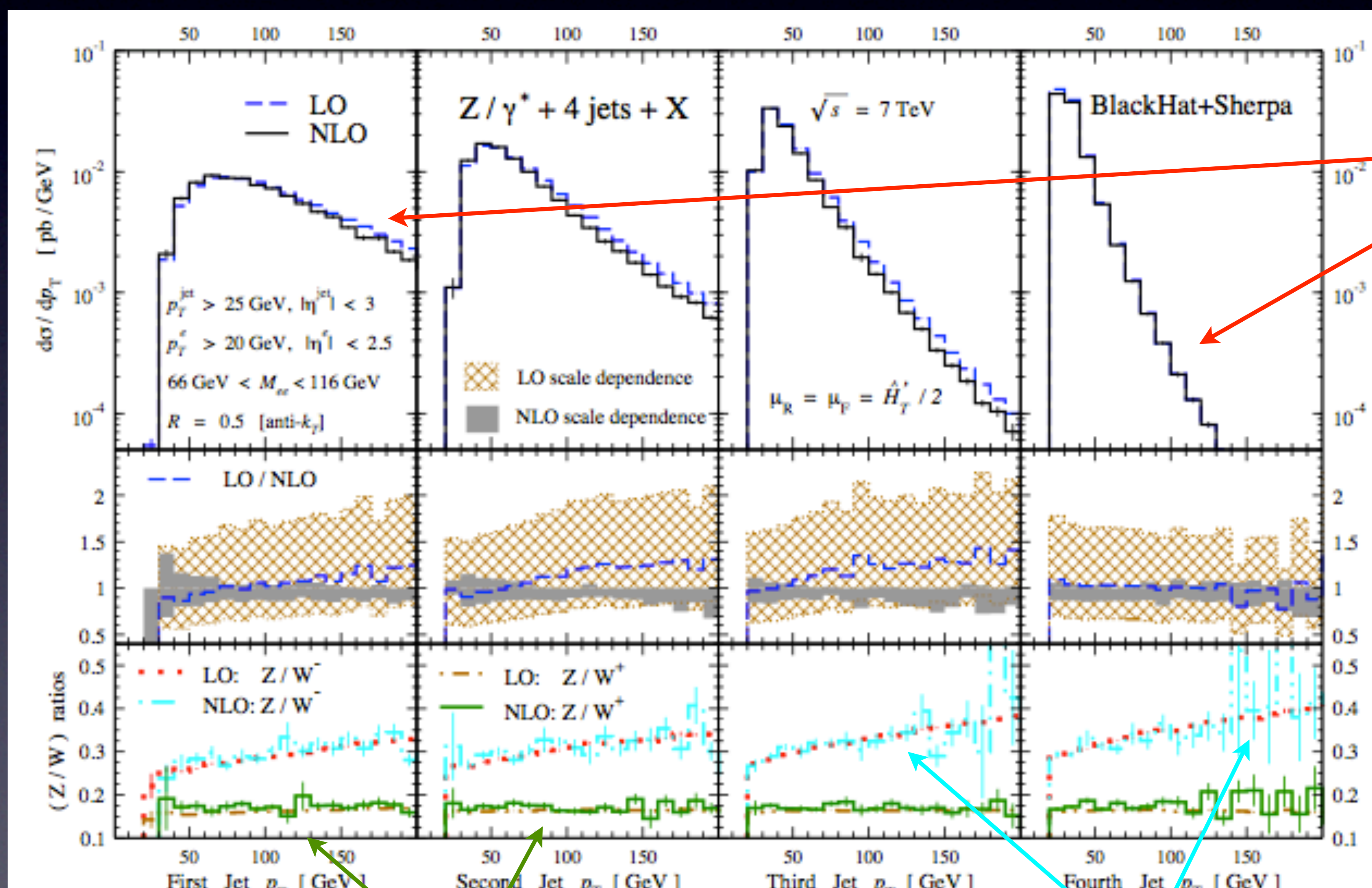
$$H_T = \sum_j p_{T,j} + p_{T,e} + p_{T,miss}$$

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

# Z + 4 jets at NLO

4 jets + MET: important background to SUSY searches

Ita et al. '11




additional jets steeper

LO/NLO not always flat

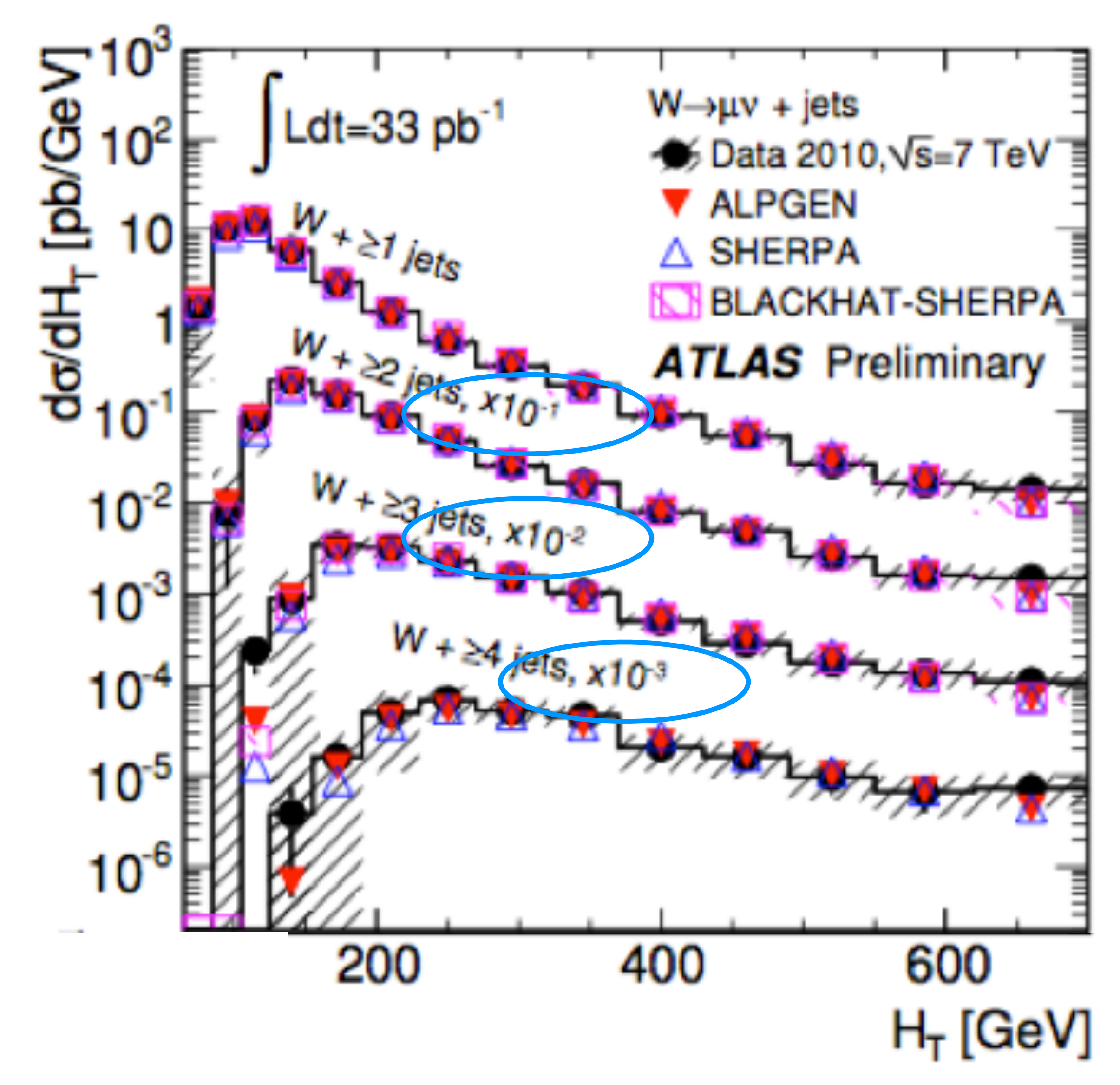
ratios: excellent PT control

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

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

# W/Z with jets

$H_T$: total transverse energy in the event




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

# 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 | ? |
| V+5j | LO | LO | ? |
| VV | NLO | NLO+PS | NNLO |
| VV+1j | LO | NLO | NLO+PS |
| VV+2j | LO | NLO(+PS) | NLO+PS ? |
| VV+3j | LO | LO | NLO |

# Automation of NLO with MadLoop

Hirschi et al. 1103.0621

- cross-checks with 2 → 2, 3
- Feynman diagrams (limited to relatively low multiplicities)
- OPP procedure for virtual
- FKS subtraction of divergences
- clever and efficient procedure for instabilities
- public code soon?
- further improvements and refinements expected soon

| | Process | $\mu$ | $n_{lf}$ | Cross section (pb) LO | 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 | $1.104 \pm 0.002$ | $1.036 \pm 0.002$ |

# Automation of NLO with GoSam

Cullen et al. 1111.2034

- cross-checks with 2 → 2, 3
- Feynman diagrams (limited to relatively low multiplicities)
- OPP procedure or tensor reduction for virtual
- interface to programs that calculate the real radiation part
- different systems to detect and rescue numerical instabilities
- public code available

http://projects.hepforge.org/gosam

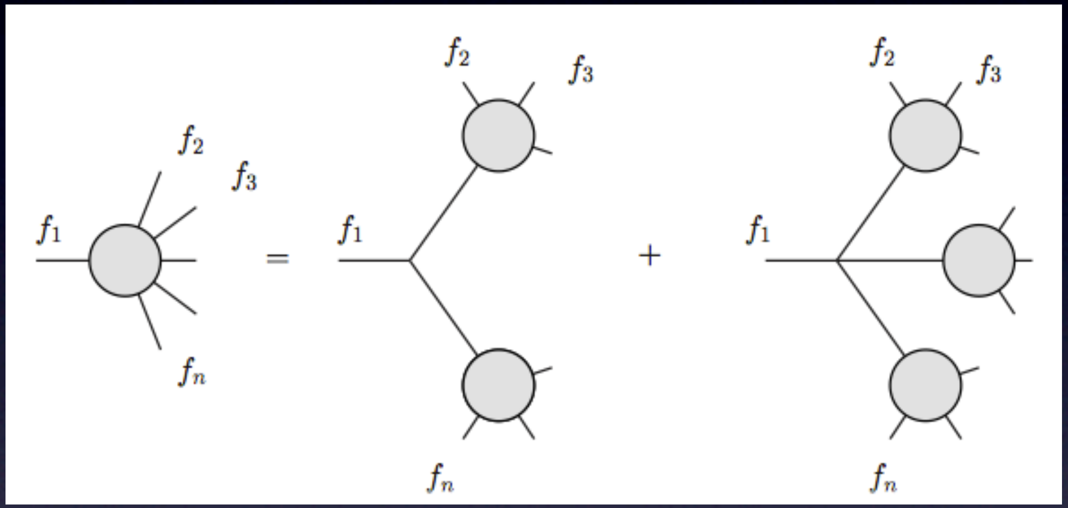
| Process | Generation [s] | Evaluation [ms] |
|---|---|---|
| $bg \to Hb$ | 236 | 2.49 |
| $d\bar{d} \to t\bar{t}$ | 341 | 4.71 |
| $d\bar{d} \to t\bar{t}$ (DRED) | 324 | 4.05 |
| $dg \to dg$ | 398 | 3.08 |
| $dg \to dg$ (DRED) | 402 | 3.28 |
| $e^+e^- \to t\bar{t}$ | 221 | 1.27 |
| $e^+e^- \to t\bar{t}$ (LanHEP) | 180 | 1.27 |
| $e^+e^- \to u\bar{u}$ | 122 | 0.65 |
| $e^+e^- \to u\bar{u}$ (AutoTools) | 173 | 0.64 |
| $gg \to gg$ | 525 | 1.69 |
| $gg \to gg$ (DRED) | 428 | 1.66 |
| $gg \to gg$ (LanHep) | 1022 | 1.70 |
| $gg \to gZ$ | 529 | 15.18 |
| $gg \to t\bar{t}$ | 1132 | 24.65 |
| $gg \to t\bar{t}$ (DRED) | 957 | 30.13 |
| $gg \to t\bar{t}$ (UFO) | 1225 | 29.45 |
| $H \to \gamma\gamma$ | 140 | 0.24 |
| $gb \to e^-\bar{\nu}_e t$ | 337 | 2.89 |
| $u\bar{d} \to e^-\bar{\nu}_e$ | 71 | 0.09 |
| $u\bar{d} \to e^-\bar{\nu}_e g$ | 154 | 1.15 |
| $u\bar{u} \to d\bar{d}$ | 186 | 2.06 |
| $\bar{u}d \to W^+W^+\bar{c}s$ | 1295 | 17.37 |
| $\gamma\gamma \to \gamma\gamma$ | 597 | 6.08 |

# Automation of NLO with Helac-NLO

Bevilacqua et al. 1110.1499

- cross-checks with 2 → 2, 3
- OPP procedure (Helac + Cuttols) for virtual
- tree amplitudes computed recursively
- interface to Helac-Dipole for the real radiation part
- program successfully used in many applications
- public code available

http://helac-phegas.web.cern.ch/helac-phegas




$$
\begin{aligned}
N(q) = & \sum_{i_0<i_1<i_2<i_3}^{m-1} \left[d(i_0 i_1 i_2 i_3) + \tilde{d}(q; i_0 i_1 i_2 i_3)\right] \prod_{i\neq i_0,i_1,i_2,i_3}^{m-1} D_i \\
& + \sum_{i_0<i_1<i_2}^{m-1} \left[c(i_0 i_1 i_2) + \tilde{c}(q; i_0 i_1 i_2)\right] \prod_{i\neq i_0,i_1,i_2}^{m-1} D_i \\
& + \sum_{i_0<i_1}^{m-1} \left[b(i_0 i_1) + \tilde{b}(q; i_0 i_1)\right] \prod_{i\neq i_0,i_1}^{m-1} D_i \\
& + \sum_{i_0}^{m-1} \left[a(i_0) + \tilde{a}(q; i_0)\right] \prod_{i\neq i_0}^{m-1} D_i \\
& + \tilde{P}(q) \prod_{i}^{m-1} D_i \,.
\end{aligned}
$$

# 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 (PS). Difficult because need to avoid double counting

# 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 (PS). Difficult because need to avoid double counting

Working frameworks

- MC@NLO
  Frixione & Webber '02 and later refs.
- POWHEG
  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
- H + 1 jet ...

[ ... ]

# POWHEG BOX

POWHEG BOX: framework to automatically shower NLO calculations using the POWHEG method

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

# POWHEG BOX

POWHEG BOX: framework to automatically shower NLO calculations using the POWHEG method

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

First application to a 2 → 4 process: $pp \to W^+W^+$ + 2 jets

An exotic SM process

Melia, Nason, Rontsch, GZ 1102.4846

- finite without any jet cut
- distinct signature in leptonic channel: same sign leptons, MET + 2 jets
- background to NP searches, also relevant for MPI studies

# POWHEG BOX

POWHEG BOX: framework to automatically shower NLO calculations using the POWHEG method

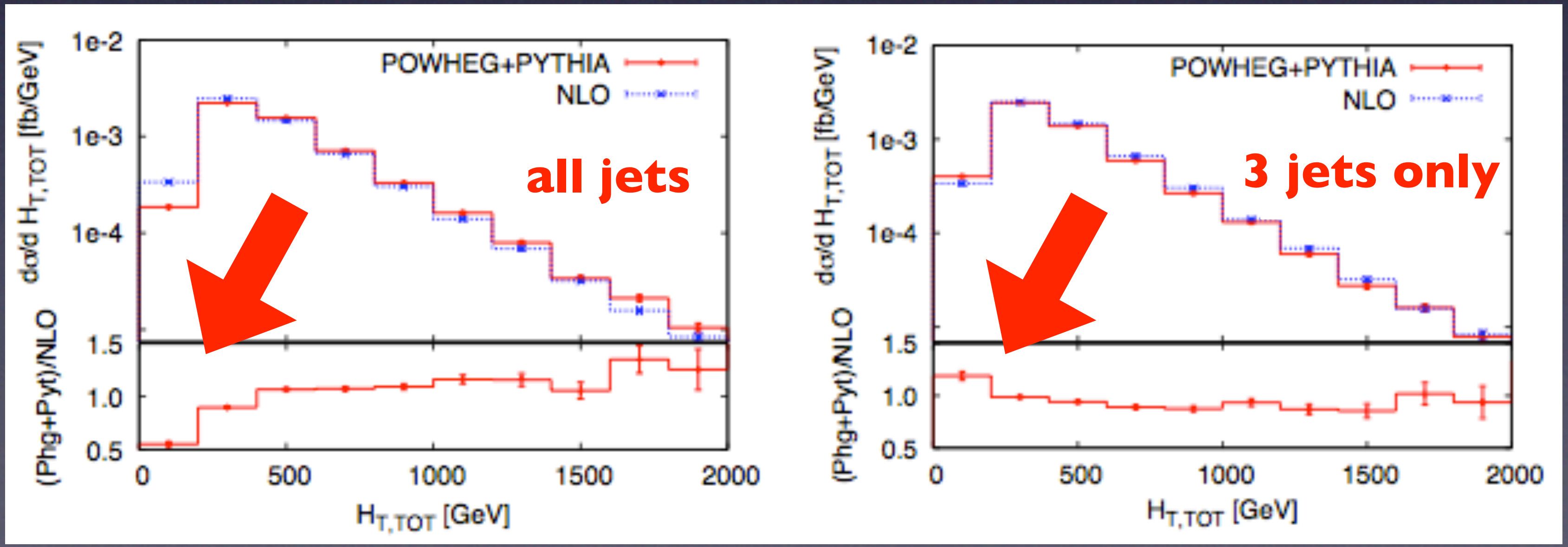
Alioli et al. 1002.2581; http://powhegbox.mib.infn.it

First application to a 2 → 4 process: pp → $W^+W^+$ + 2 jets

An exotic SM process

Melia, Nason, Rontsch, GZ 1102.4846

- finite without any jet cut
- distinct signature in leptonic channel: same sign leptons, MET + 2 jets
- background to NP searches, also relevant for MPI studies




☛ the level of agreement depends on the observable

# W + 2 jets in aMC@NLO

Hirschi et al. 1104.5613

Very recent theoretical development:

aMC@NLO = automated complete event generation at NLO

# W + 2 jets in aMC@NLO

Hirschi et al. 1104.5613

Very recent theoretical development:
aMC@NLO = automated complete event generation at NLO

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

- 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

# W + 2 jets in aMC@NLO

Very recent theoretical development:

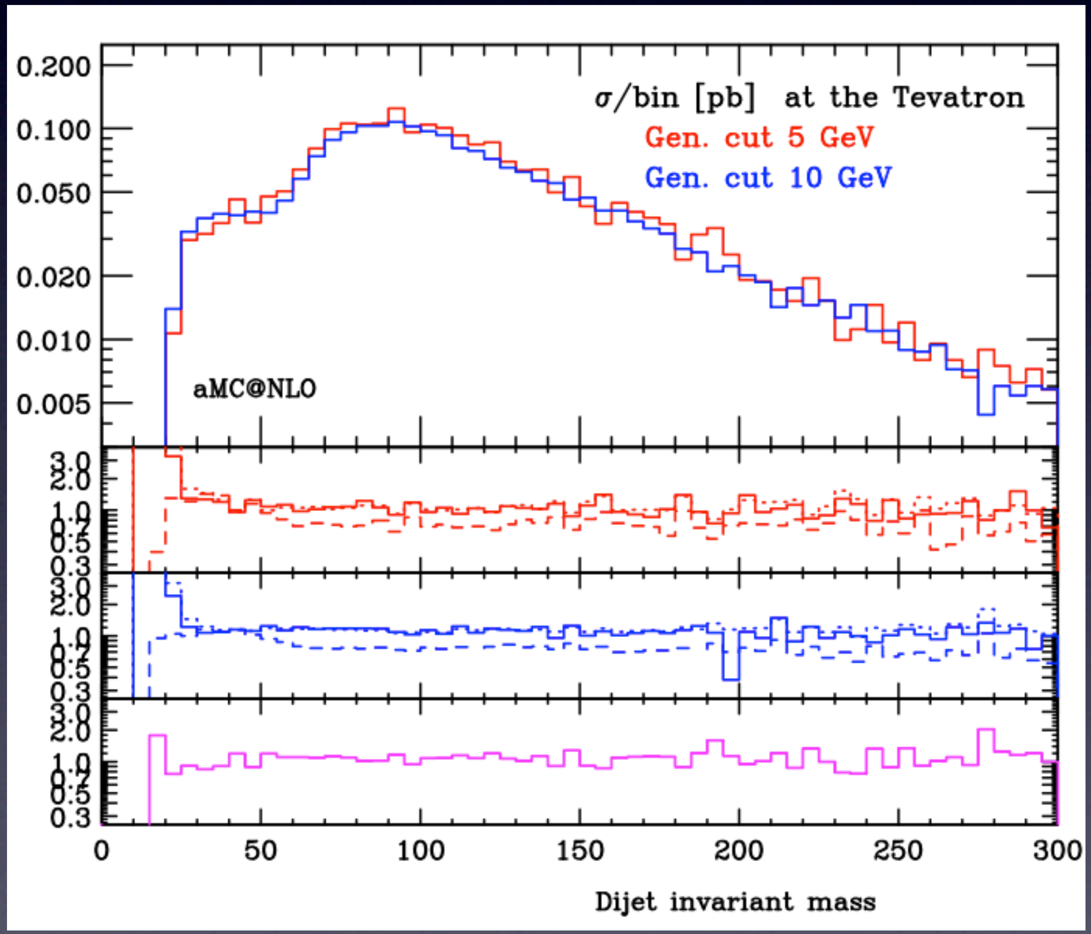
Hirschi et al. 1104.5613

aMC@NLO = automated complete event generation at NLO

Frederix et al. 1110.5502

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

- 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




Ratio to NLO (LO) solid (dashed)

<u>Result:</u>

no enhancement over (N)LO or LO+PS in the mass range 130-160 GeV

# W/Z + bb in aMC@NLO

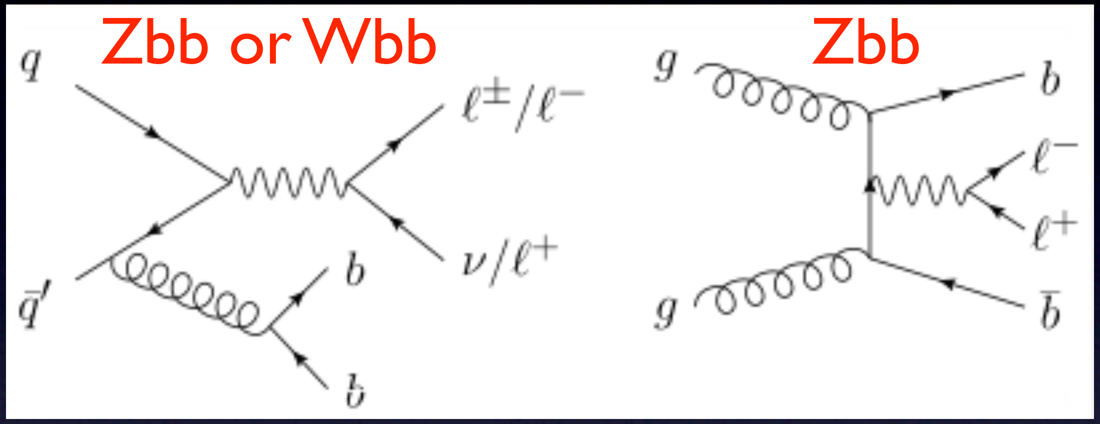
Accuracy: NLO+PS, with spin correlations, heavy-quark mass effects

Frederix et al. 1106.6019

# W/Z + bb in aMC@NLO

Accuracy: NLO+PS, with spin correlations, heavy-quark mass effects

Frederix et al. 1106.6019

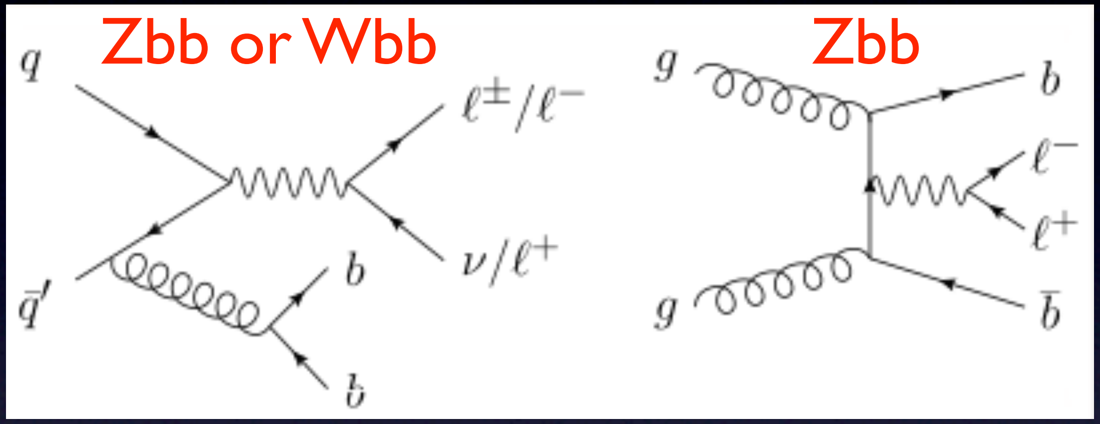



gg channel present at LO only for Zbb. Most differences Wbb vs. Zbb at the LHC due to this

# W/Z + bb in aMC@NLO

Accuracy: NLO+PS, with spin correlations, heavy-quark mass effects

Frederix et al. 1106.6019




gg channel present at LO only for Zbb. Most differences Wbb vs. Zbb at the LHC due to this

| | Cross section (pb) | | | | | |
|---|---|---|---|---|---|---|
| | Tevatron $\sqrt{s}$ =1.96 TeV | | | LHC $\sqrt{s}$ =7 TeV | | |
| | LO | NLO | $K$ factor | LO | NLO | $K$ factor |
| $\ell\nu b\bar{b}$ | 4.63 | 8.04 | 1.74 | 19.4 | 38.9 | 2.01 |
| $\ell^+\ell^- b\bar{b}$ | 0.860 | 1.509 | 1.75 | 9.66 | 16.1 | 1.67 |

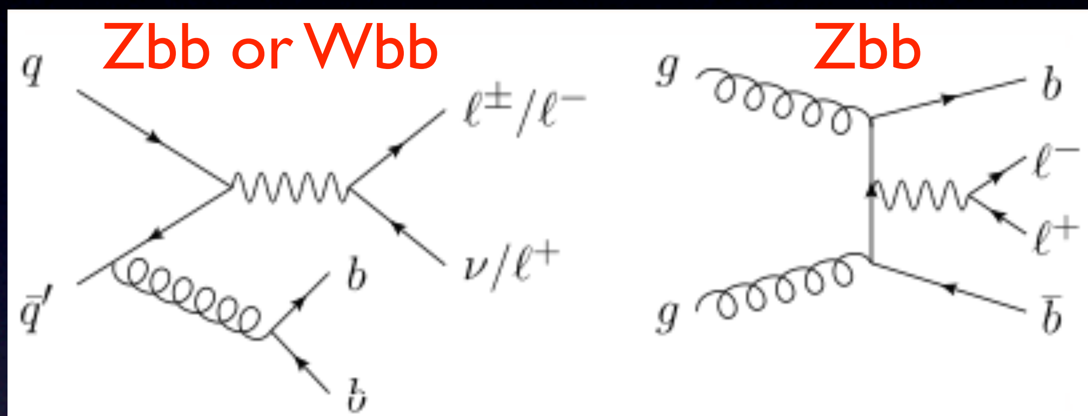
Wbb/Zbb: $\approx 5$ $\approx 2$

Reason: gg enhancement in Zbb at the LHC

# W/Z + bb in aMC@NLO

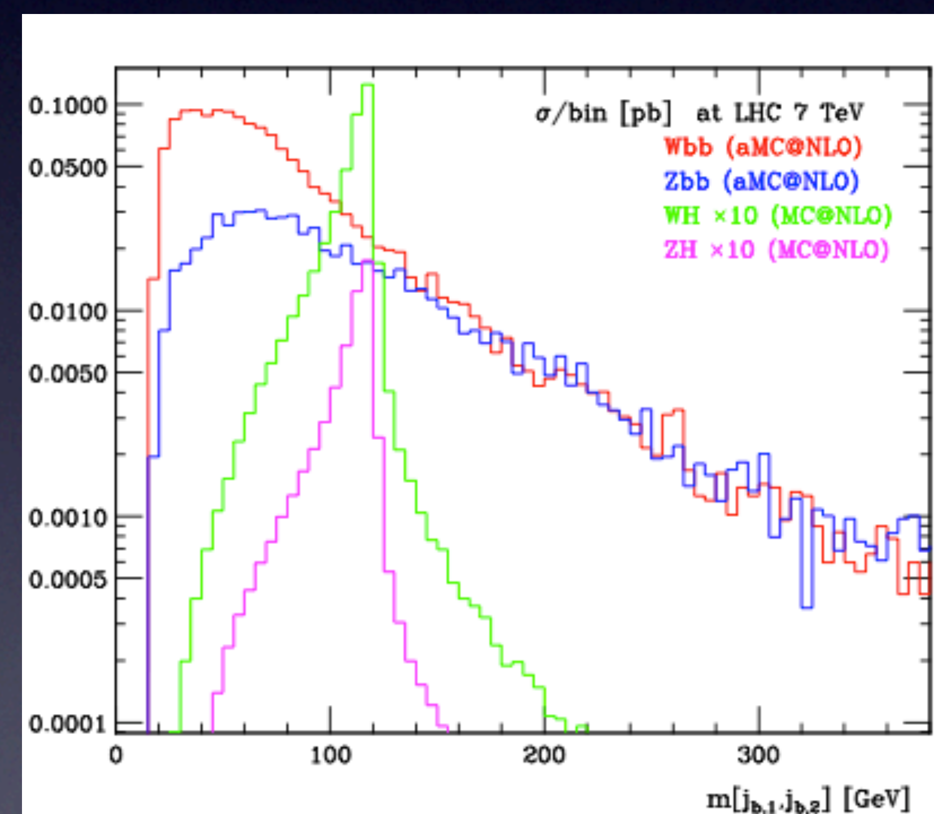
Accuracy: NLO+PS, with spin correlations, heavy-quark mass effects

Frederix et al. 1106.6019




gg channel present at LO only for Zbb. Most differences Wbb vs. Zbb at the LHC due to this

**Example**: signal & background with the same acccuracy




| | Cross section (pb) | | | | | |
|---|---|---|---|---|---|---|
| | Tevatron $\sqrt{s}$ =1.96 TeV | | | LHC $\sqrt{s}$ =7 TeV | | |
| | LO | NLO | $K$ factor | LO | NLO | $K$ factor |
| $\ell\nu b\bar{b}$ | 4.63 | 8.04 | 1.74 | 19.4 | 38.9 | 2.01 |
| $\ell^+\ell^- b\bar{b}$ | 0.860 | 1.509 | 1.75 | 9.66 | 16.1 | 1.67 |

Wbb/Zbb: $\approx 5$ $\approx 2$

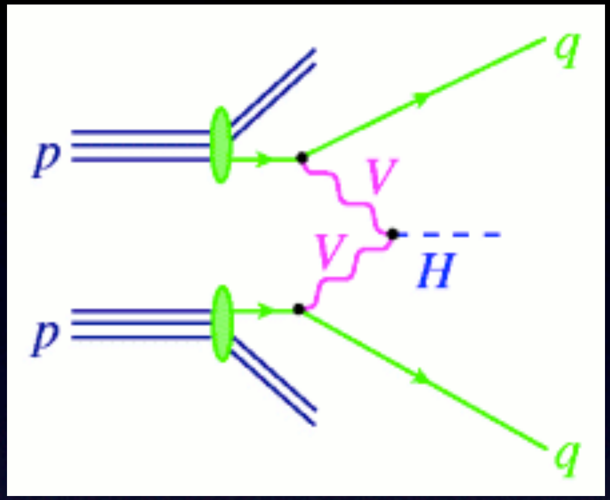
Reason: gg enhancement in Zbb at the LHC

NLO (mb≠0): Cordero, Reina, Wackeroth '06 (no W decay)
Badger, Campbell, Ellis '11 (with W decay in MCFM)
Also in POWHEG: Oleari, Reina 1105.4488

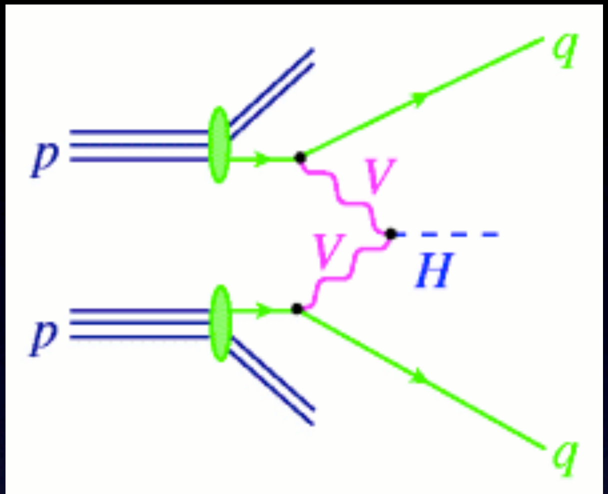
# VBF processes

Suppressed color exchange between quark lines

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



# VBF processes




Suppressed color exchange between quark lines

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

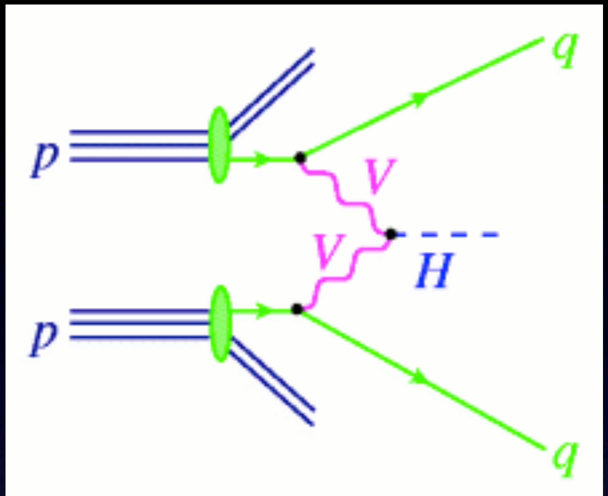
Physics of Vector-Boson-Fusion (VBF) processes is very rich.
Unique window at EW symmetry breaking.

A proper discussion would need a dedicated talk

# 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.
Unique window at EW symmetry breaking.

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:

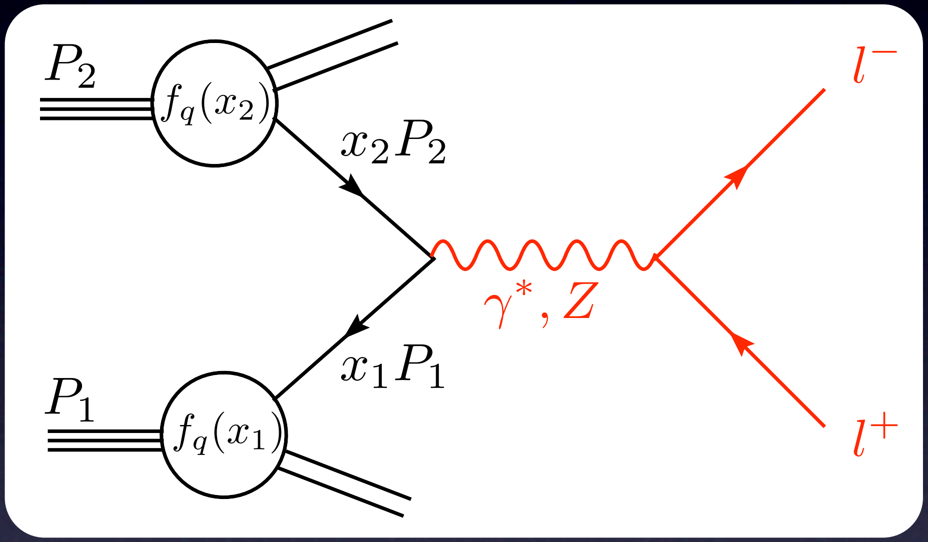
- new processes: jj$\gamma$, WZj W$\gamma$j, WW$\gamma$ ZZ$\gamma$, WZ$\gamma$, W$\gamma\gamma$, Z$\gamma\gamma$, $\gamma\gamma\gamma$
- anomalous (quartic) couplings
- extension to MSSM

# Drell-Yan

Drell-Yan processes: Z/W production ($W \to l\nu$, $Z \to l^+l^-$)

Golden-processes in QCD 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

parton distribution functions (PDFs) | partonic cross-section | hadronization corrections

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

known to NNLO | known to NNLO

# Drell-Yan

Best known process at the LHC

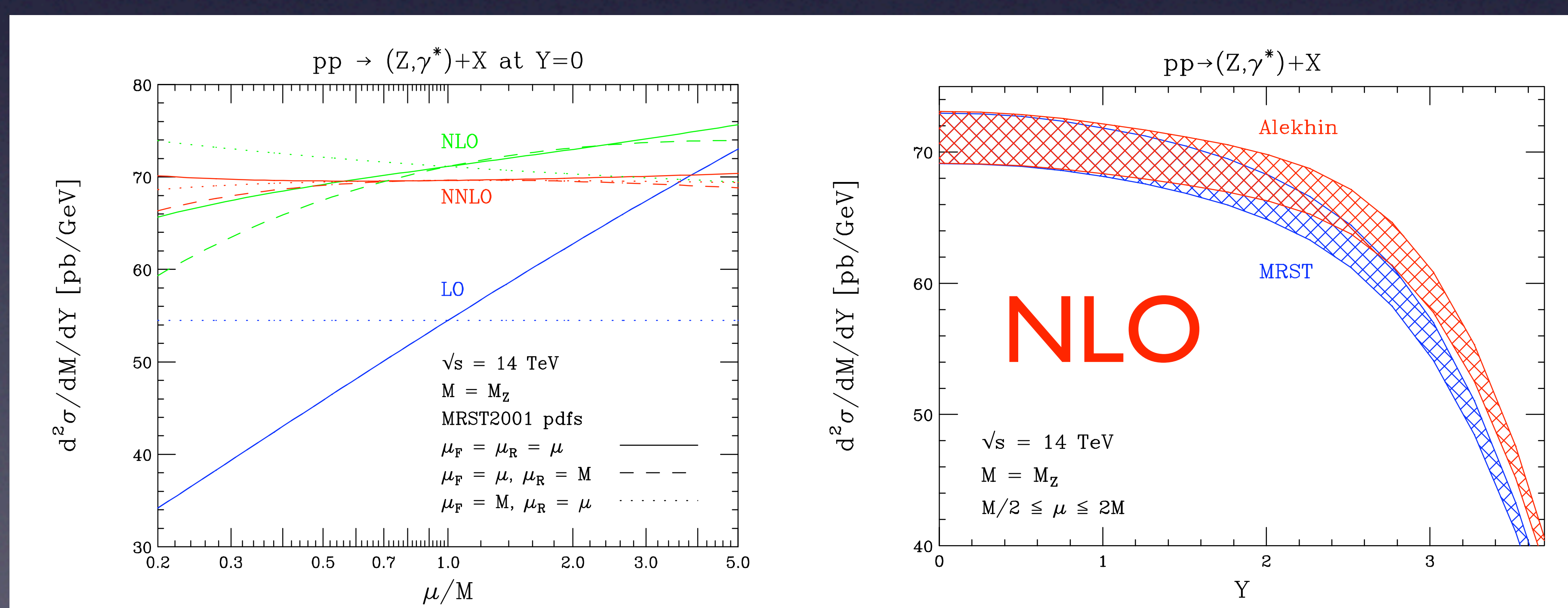
✓ known at NNLO in QCD, fully differential in lepton momenta including spin-correlations, finite-width effects, γ-Z interference

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

✓ also NNLL transverse momentum resummation and soft gluon resummation (ResBos)

ResBos Balazs and Yuan ‘97; Bozzi et al. ’11

Scale stability and sensitivity to PDFs




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

# Drell-Yan

Best known process at the LHC

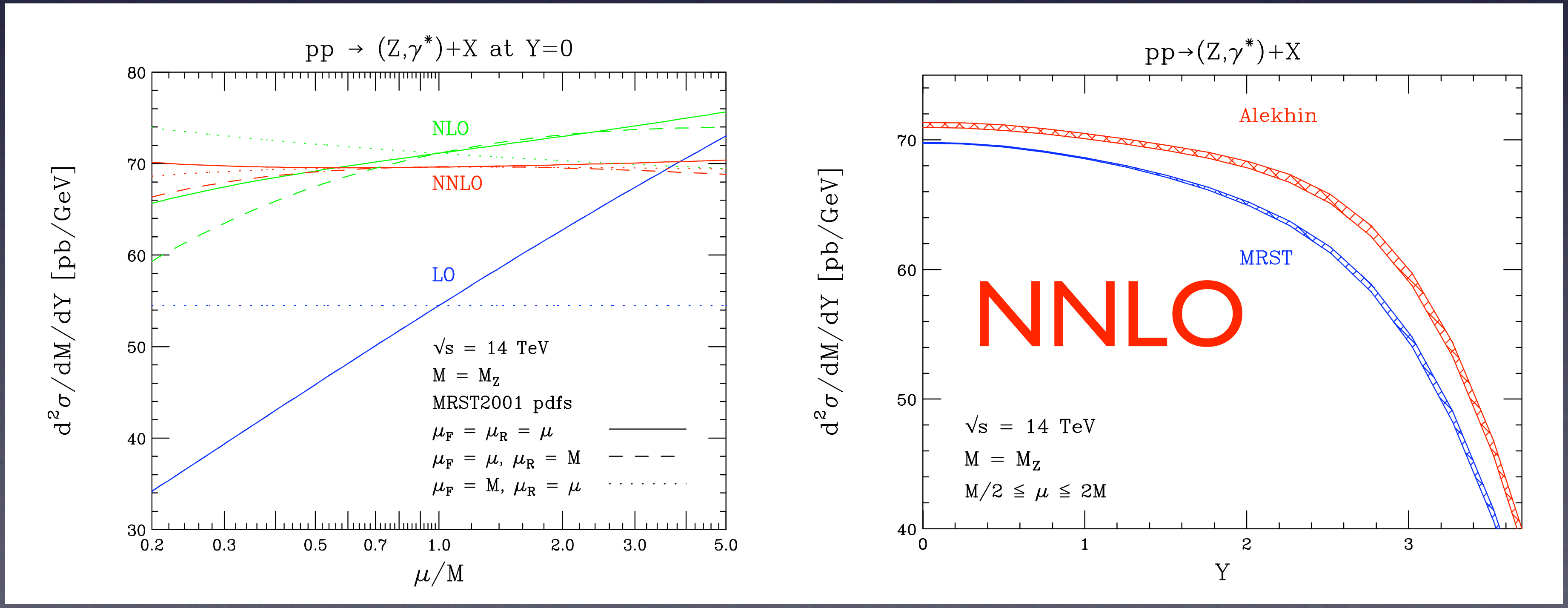
✓known at NNLO in QCD, fully differential in lepton momenta including spin-correlations, finite-width effects, γ-Z interference

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

✓also NNLL transverse momentum resummation and soft gluon resummation (ResBos)

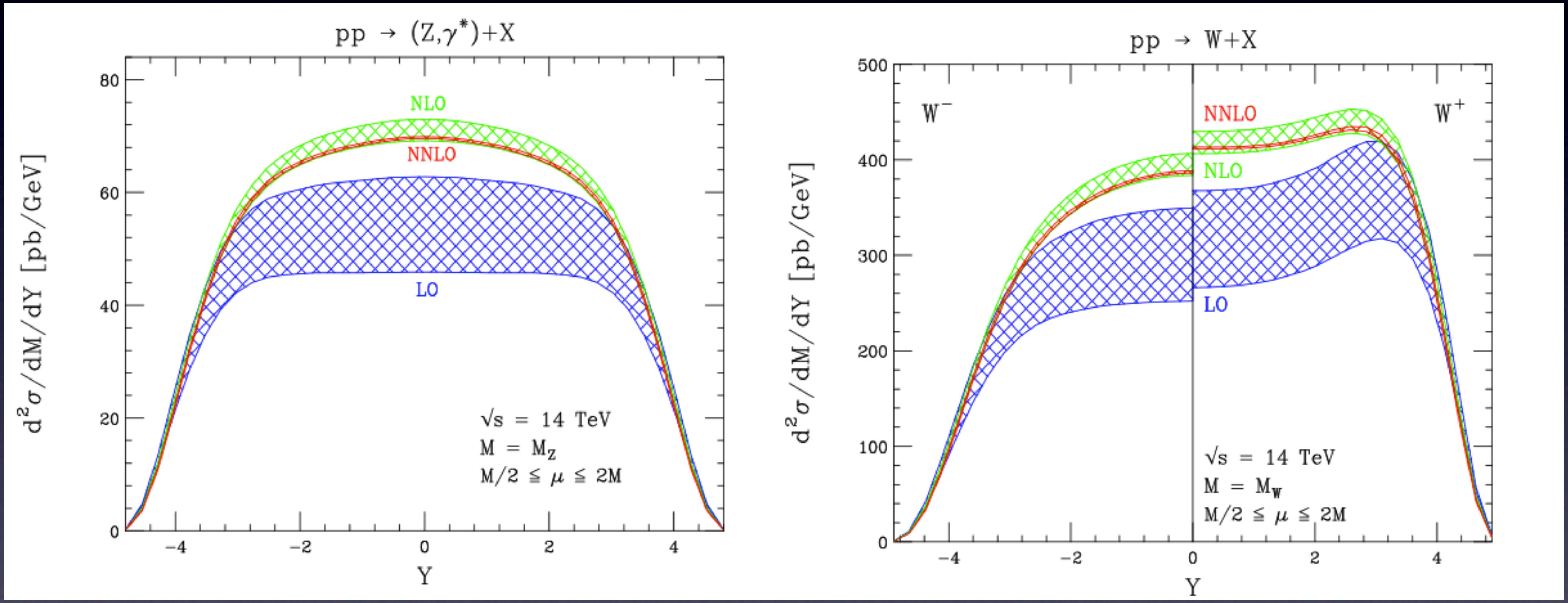
ResBos Balazs and Yuan '97; Bozzi et al. '11

Scale stability and sensitivity to PDFs




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

# Rapidity distributions

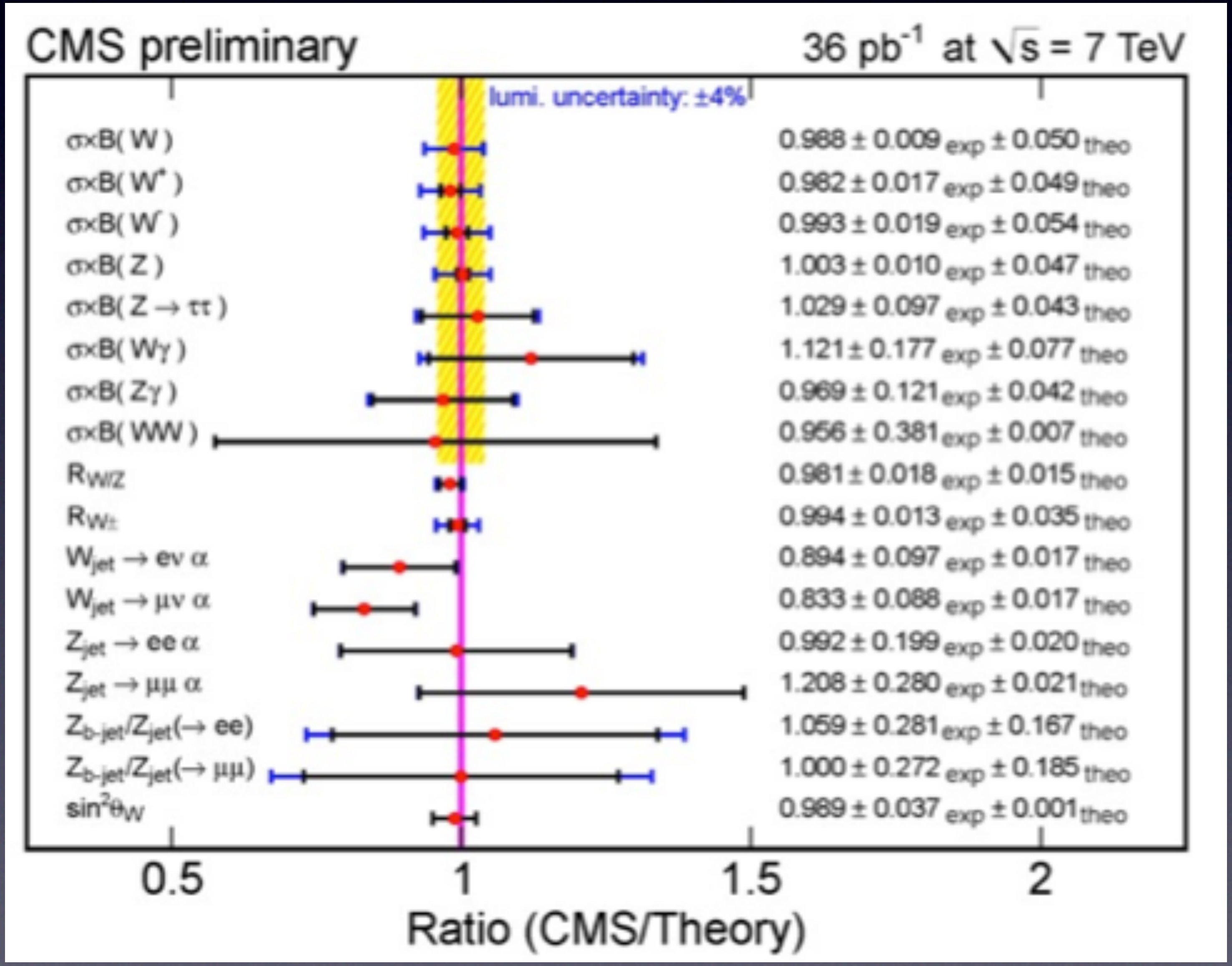



Anastasiou, Dixon, Melnikov, Petriello '03, '05; Melnikov, Petriello '06

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

# NNLO vs. LHC data

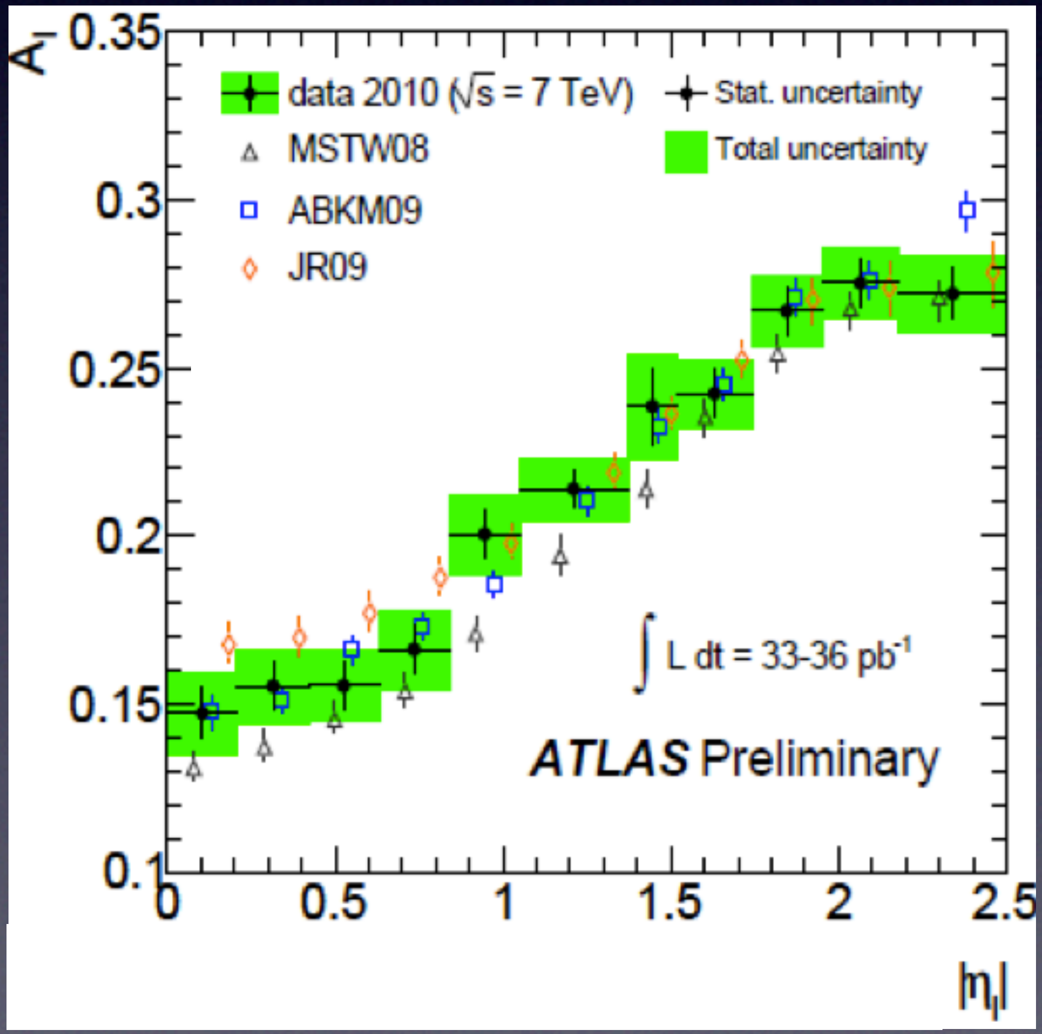
Spectacular experimental achievements in very little time!




- remarkable agreement with theory
- precise measurement of W/Z properties (also notice measurement of $\sin^2\theta_W$)
- achieved control and precision already allows improvements on PDFs (see later)

# 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

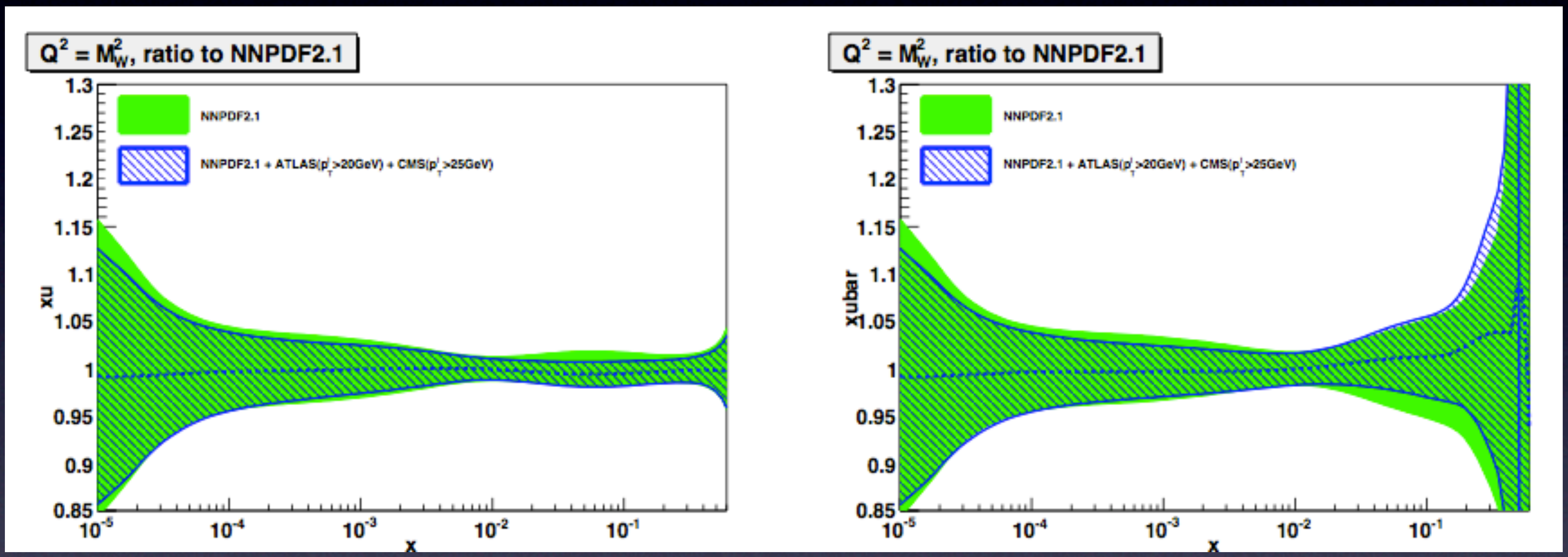



$$A(\eta) = \frac{R_W(\eta) - 1}{R_W(\eta) + 1}$$

- measurement very sensitive to PDFs since many uncertainties cancel in ratios
- good agreement with various PDFs but very sensitive to shape details
- similar results by CMS (not shown here)

# Charge asymmetry

Effect of ATLAS and CMS lepton charge asymmetry on NNPDF global fit




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 distributions

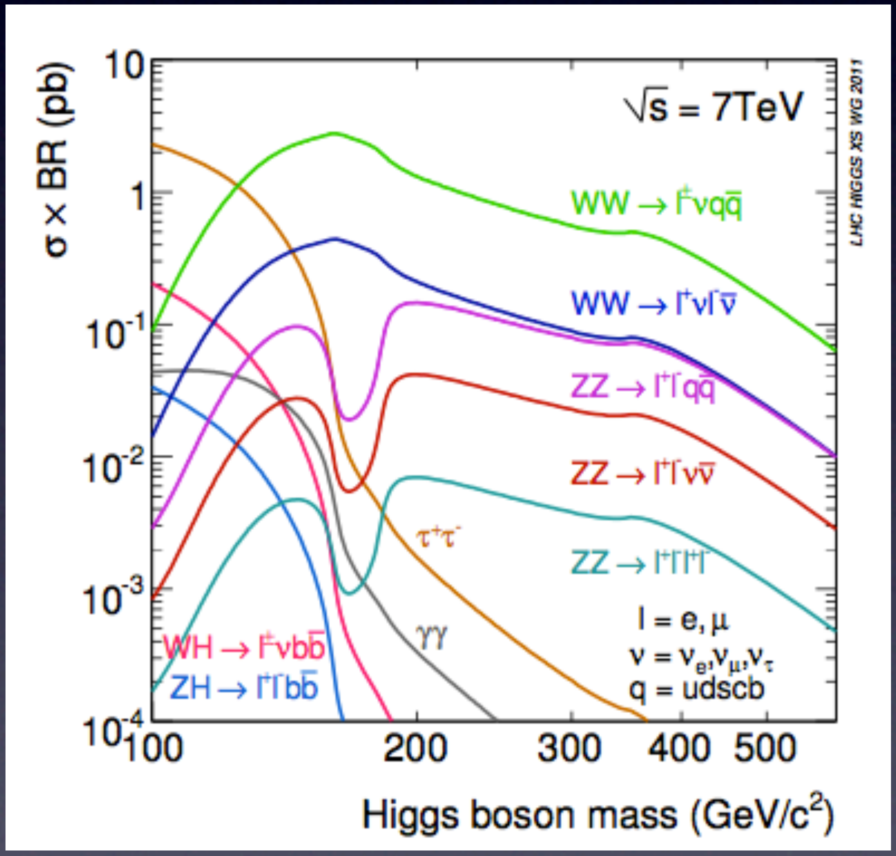
NNPDF 1108.1758

NB:
LHCb data at larger rapidities probe larger and smaller values of x that are less constraint, they will have a larger impact than ATLAS/CMS soon

# Combined Higgs searches

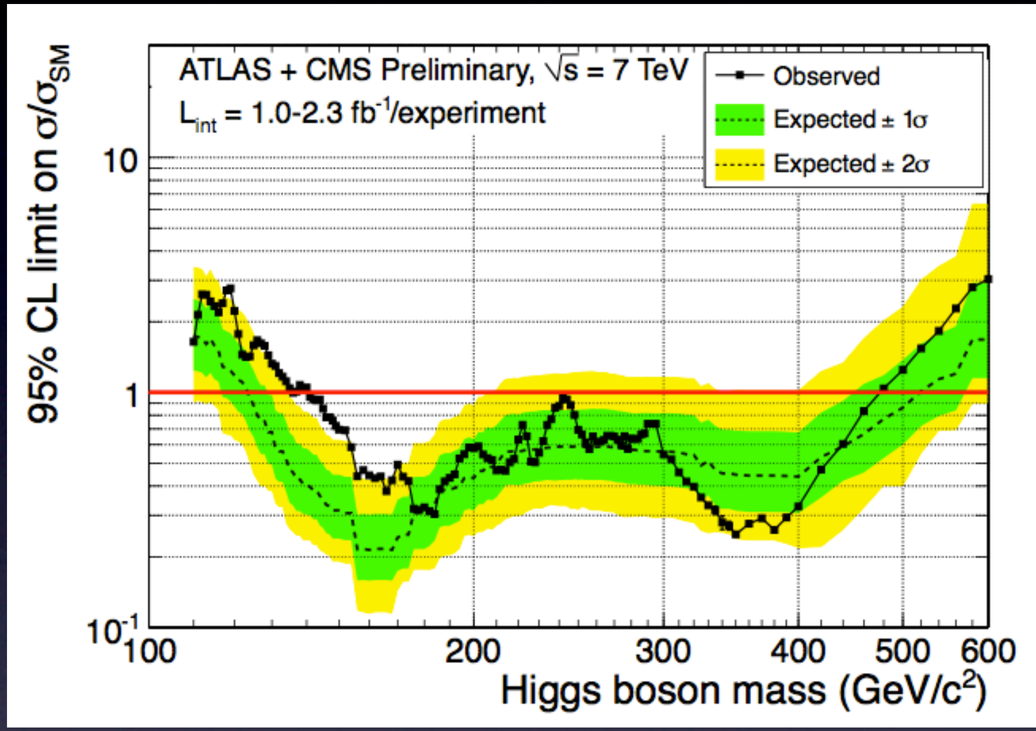
- main decay channels considered: WW→ lνlν, ZZ→ 4l, ZZ→ llνν, ZZ→ llqq, ZZ→ llττ, ττ, bb, γγ
- 67 independent sub-channels considered in the full mass range 110-600 GeV
- integrated luminosity 1.0-2.3 $fb^{-1}$ per experiment
- backgrounds in signal region are derived from control region with data-driven methods (but for di-boson production). Extrapolation relies on most up-to-date theory tools (DY@NNLO, FEWZ, HATHOR, MCFM, POWHEG ... )

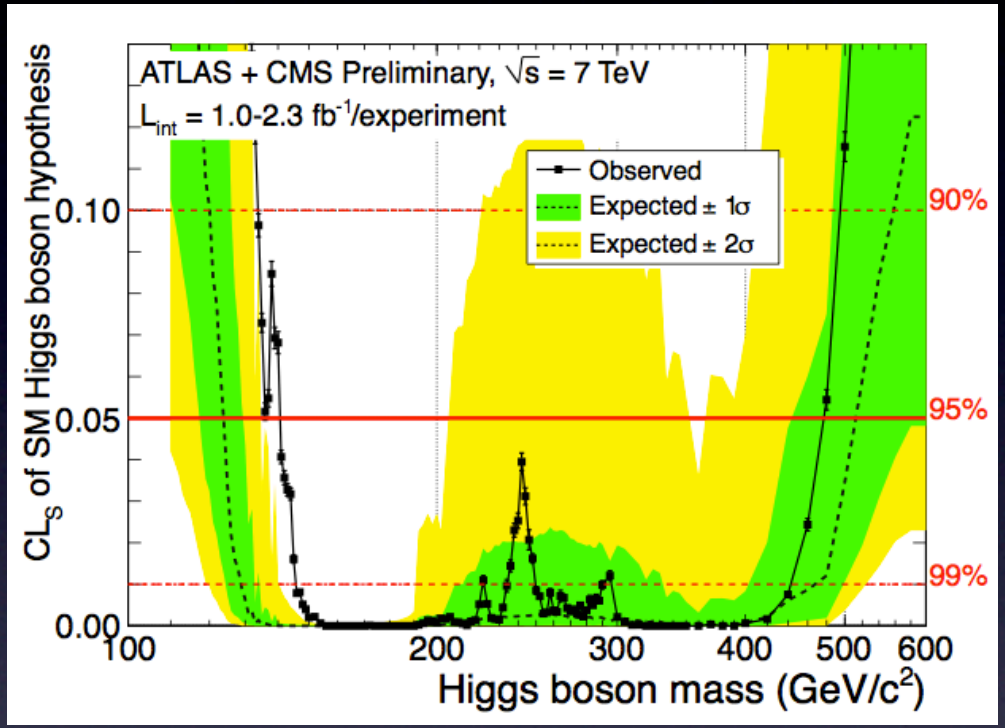
ATLAS-CONF-2001-157



# Combined Higgs searches

ATLAS-CONF-2001-157



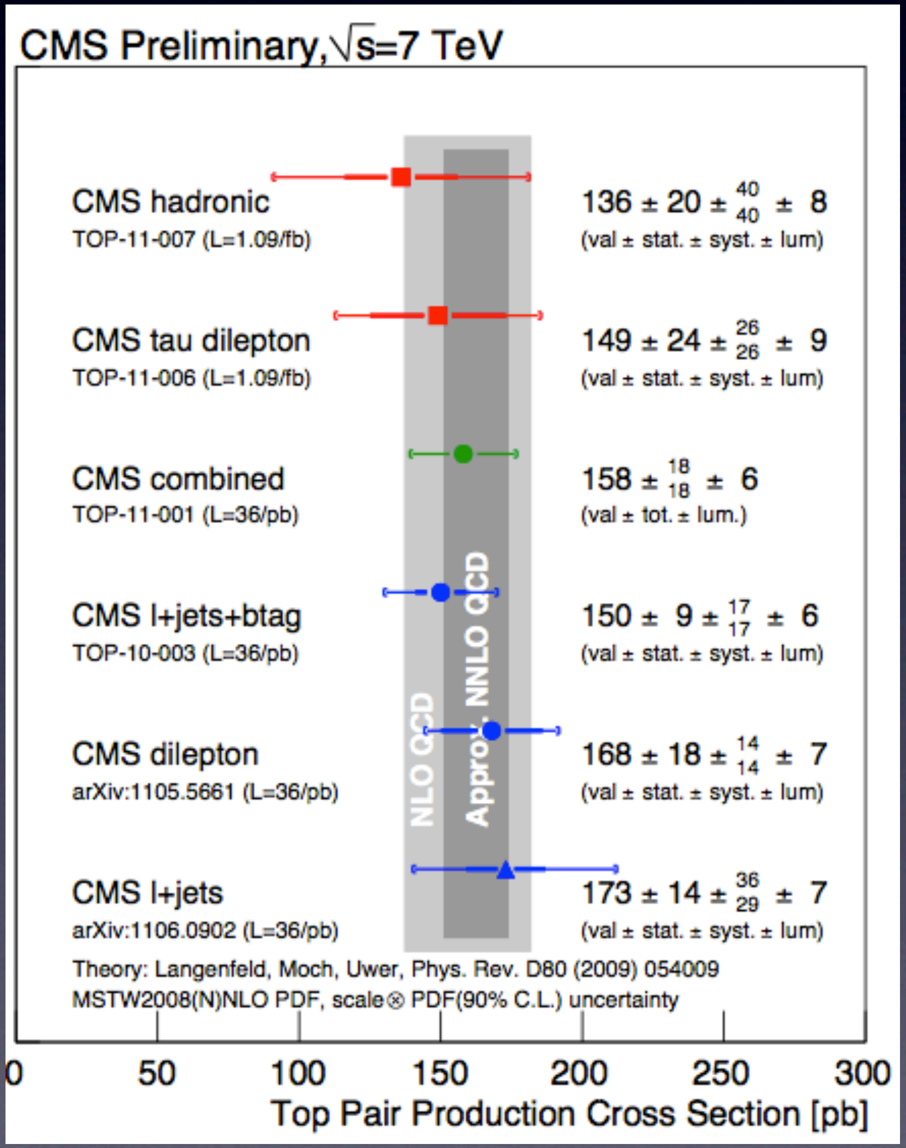

- 95%CL exclusion in the mass range 141-476 GeV [expected in the absence of signal is 124-520 GeV]
- 146-443 GeV excluded also at 99%CL, with the exception of three small regions between 220 and 320 GeV
- largest excess in the searched mass range [110-600] GeV has a significance of 1.6 σ (around 113-119 GeV) and makes the observed limits at low mass less restricted than expected

# Top

Large Yukawa coupling and prominent decay product in many new-physics models. The place where new physics will show up?

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

[ . . . ]




<u>Motivation for NNLO</u>

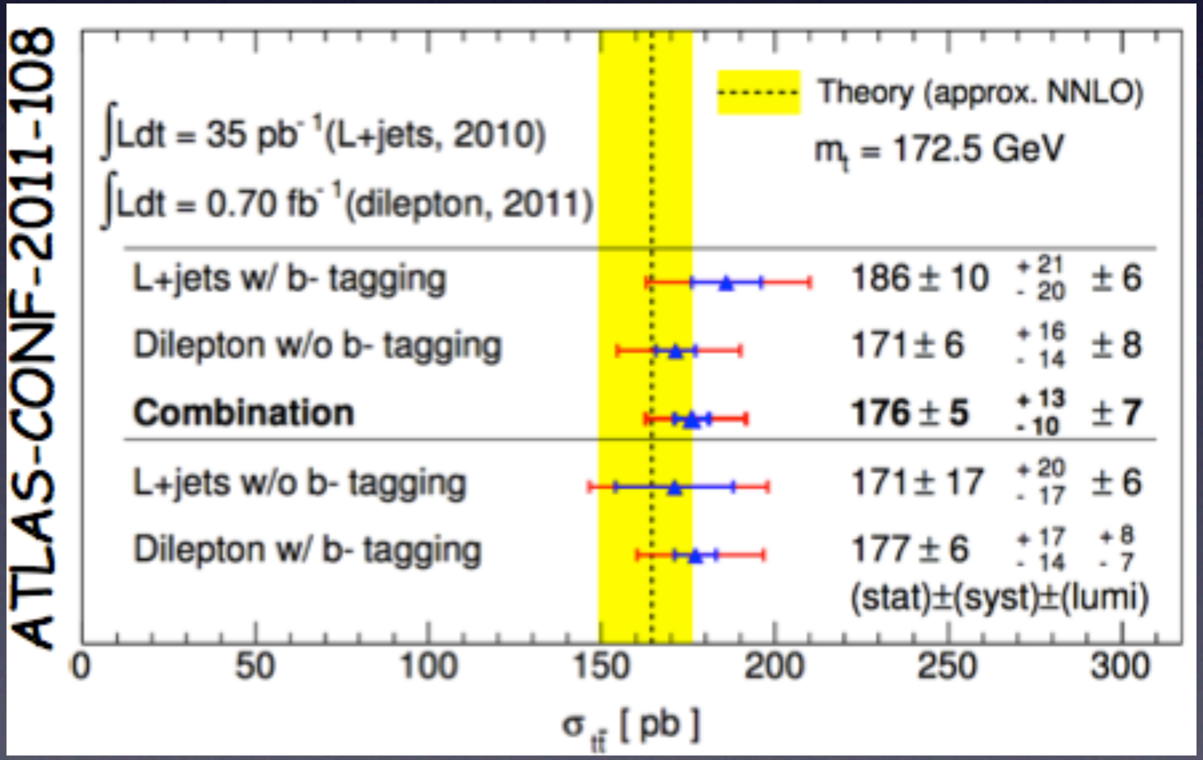
- constrain gluon pdf
- top mass from cross-section
- top FB asymmetry

# Top

Large Yukawa coupling and prominent decay product in many new-physics models. The place where new physics will show up ?

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

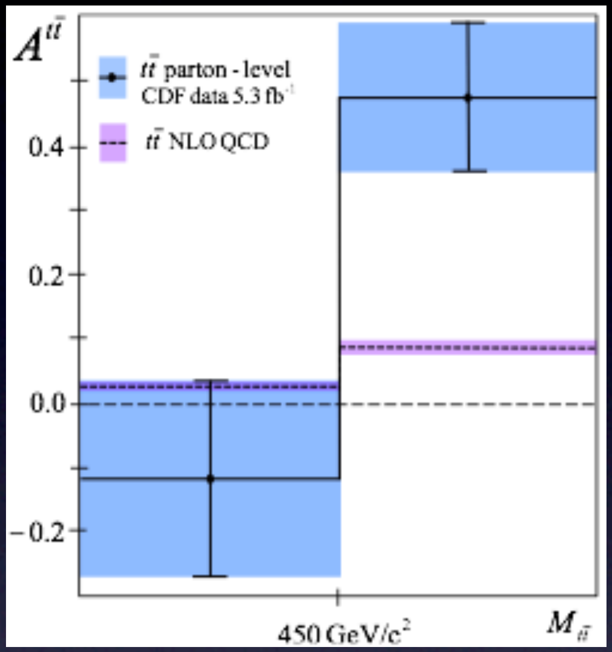
[ . . . ]




<u>Motivation for NNLO</u>

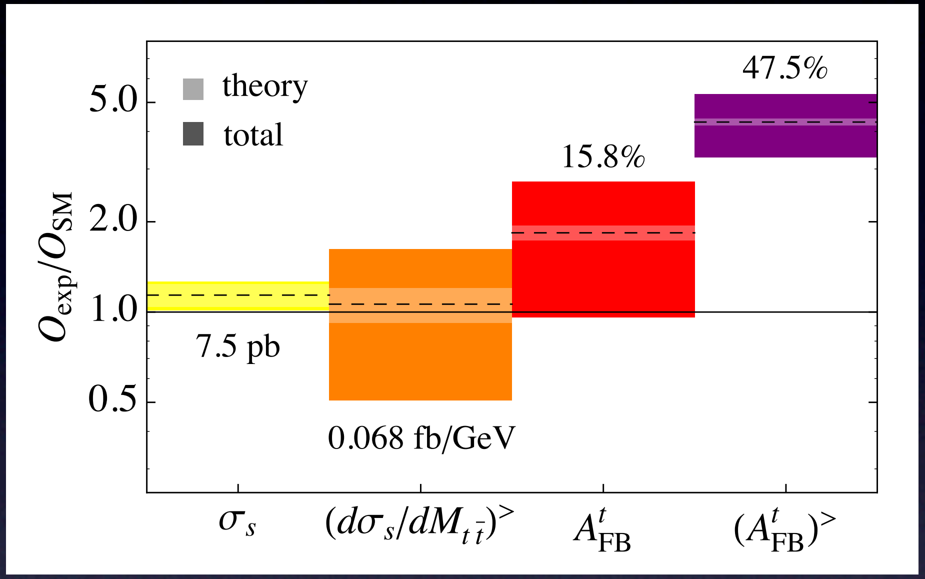
- constrain gluon pdf
- top mass from cross-section
- top FB asymmetry

# Top charge asymmetry




CDF 1101.0034

Tension between sym. and asym.




Haisch & Westhoff 1106.0529

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, ...

# Parton densities


Huge effort in understanding differences and improving theoretical and statistical treatment from all groups, reflected in new PDF sets [ABM11, CT10, HERApdfs1.6, JR, MSTW08, NNpdf2.1]

NNpdf reached full maturity, all towards NNLO, improved treatment of heavy quarks, more flexible parameterizations, dynamic tolerance, inclusion of more data in fits . . .

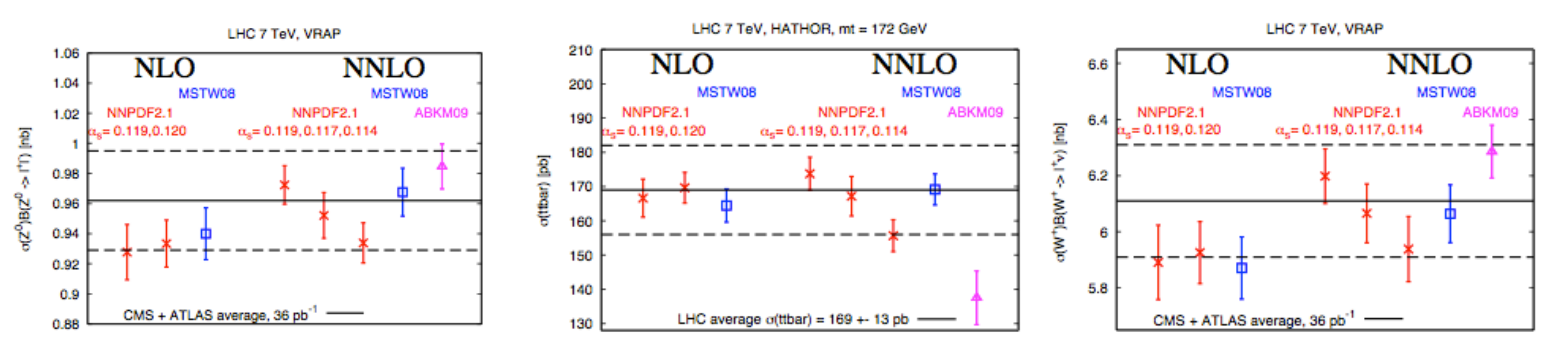
# Parton densities


Huge effort in understanding differences and improving theoretical and statistical treatment from all groups, reflected in new PDF sets [ABM11, CT10, HERApdfs1.6, JR, MSTW08, NNpdf2.1]

NNpdf reached full maturity, all towards NNLO, improved treatment of heavy quarks, more flexible parameterizations, dynamic tolerance, inclusion of more data in fits . . .

Uncertainty from pdfs and $\alpha_s$ on benchmark processes

NNpdfs 1107.2652



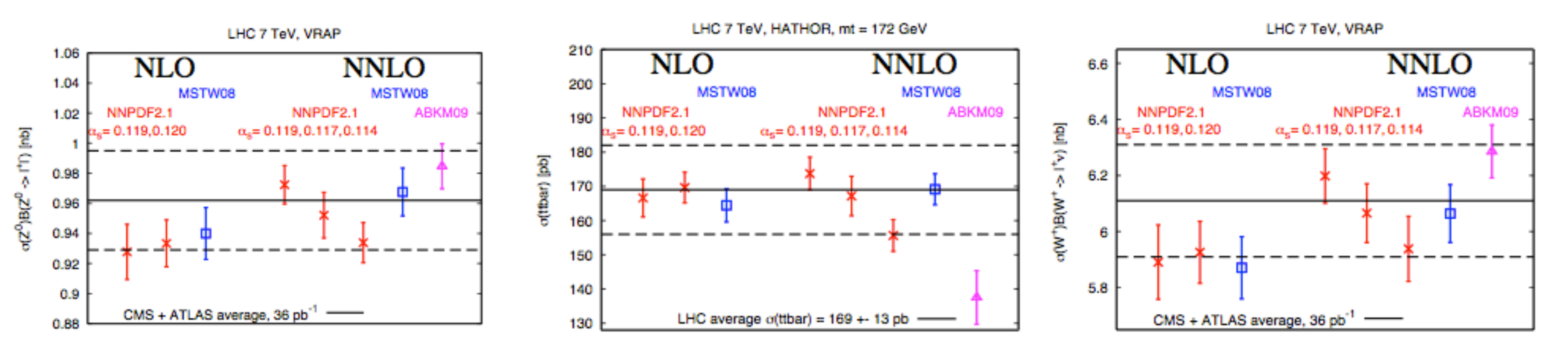
# Parton densities


Huge effort in understanding differences and improving theoretical and statistical treatment from all groups, reflected in new PDF sets [ABM11, CT10, HERApdfs1.6, JR, MSTW08, NNpdf2.1]

NNpdf reached full maturity, all towards NNLO, improved treatment of heavy quarks, more flexible parameterizations, dynamic tolerance, inclusion of more data in fits . . .

## Uncertainty from pdfs and $\alpha_s$ on benchmark processes

NNpdfs 1107.2652




Differences due to:

1) different data in fits
2) different methodology (parametrization, theory)
3) different treatment of heavy quarks
4) different $\alpha_s$

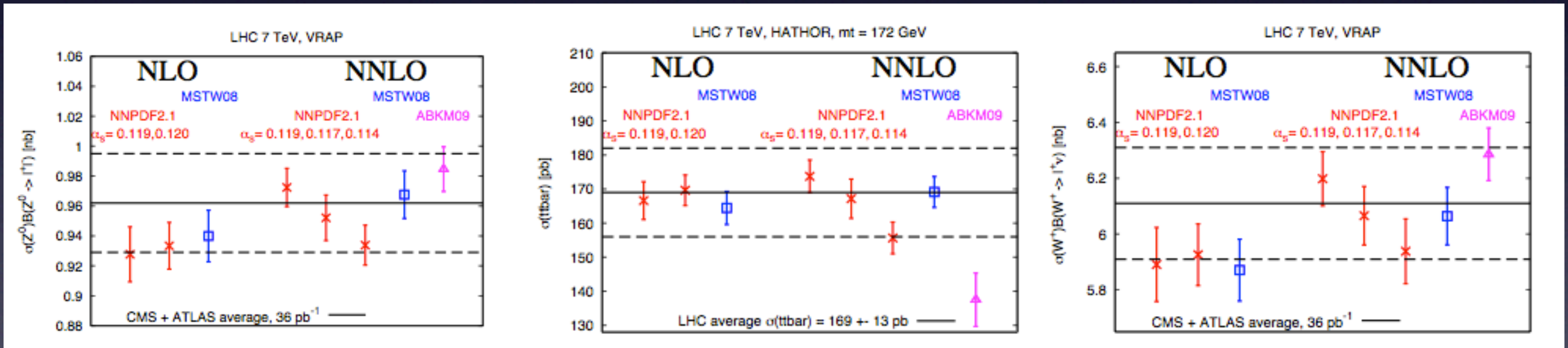
# Parton densities


Huge effort in understanding differences and improving theoretical and statistical treatment from all groups, reflected in new PDF sets [ABM11, CT10, HERApdfs1.6, JR, MSTW08, NNpdf2.1]

NNpdf reached full maturity, all towards NNLO, improved treatment of heavy quarks, more flexible parameterizations, dynamic tolerance, inclusion of more data in fits . . .

## Uncertainty from pdfs and $\alpha_s$ on benchmark processes

NNpdfs 1107.2652



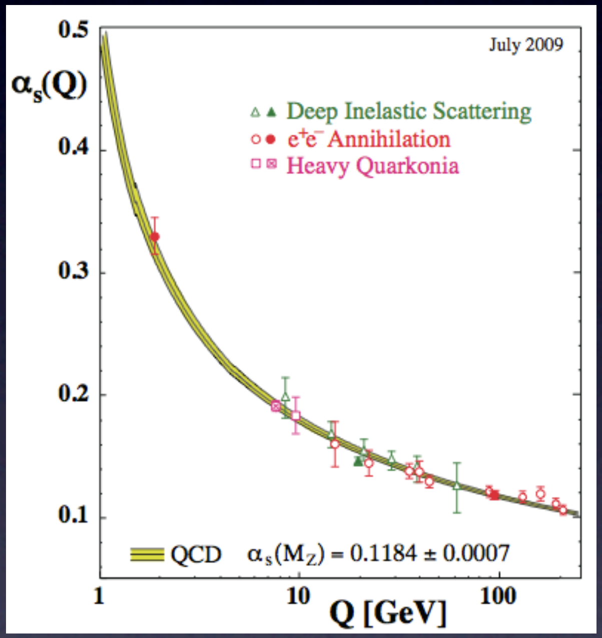

Differences due to:

1) different data in fits
2) different methodology (parametrization, theory)
3) different treatment of heavy quarks
4) different $\alpha_s$

# $\alpha_s$ in year 2011

2009 world summary

$\alpha_s = 0.1184 \pm 0.0007$




dedicated workshop in Munich in February 2011
1110.0016

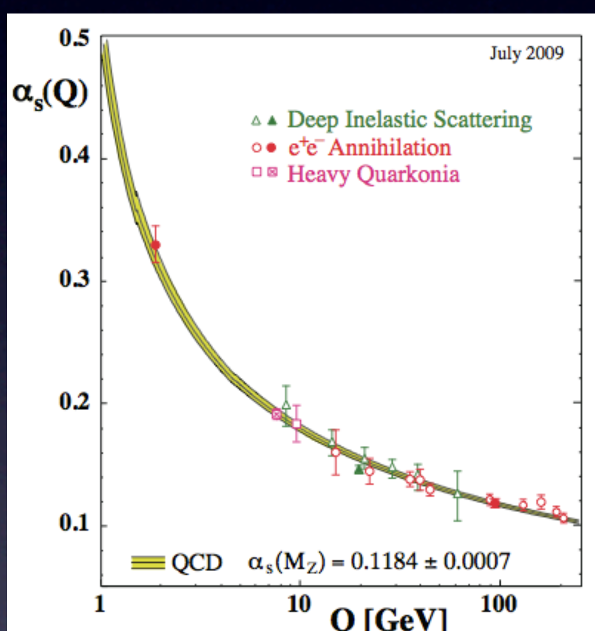
Preliminary 2011 average: $\alpha_s = 0.1183 \pm 0.0010$

| | Process | Q [GeV] | $\alpha_s(M_{Z^0})$ | excl. mean $\alpha_s(M_{Z^0})$ | std. dev. |
|---|---|---|---|---|---|
| | $\tau$-decays | 1.78 | $0.1197 \pm 0.0016$ | $0.1180 \pm 0.0011$ | 0.9 |
| | DIS [$F_2$] | 2 - 170 | $0.1142 \pm 0.0023$ | $0.1186 \pm 0.0013$ | 1.7 |
| | DIS [e-p $\rightarrow$ jets] | 6 - 100 | $0.1198 \pm 0.0032$ | $0.1182 \pm 0.0010$ | 0.5 |
| | Lattice QCD | 7.5 | $0.1183 \pm 0.0008$ | $0.1182 \pm 0.0017$ | 0.1 |
| | $\Upsilon$ decays | 9.46 | $0.119^{+0.006}_{-0.005}$ | $0.1183 \pm 0.0010$ | 0.1 |
| new | $e^+e^-$ [jets & shps] | 14 - 44 | $0.1172 \pm 0.0051$ | $0.1183 \pm 0.0010$ | 0.2 |
| → | $p\bar{p}$ incl. jets | 50-145 | $0.1161 \pm 0.0045$ | $0.1183 \pm 0.0010$ | 0.4 |
| | $e^+e^-$ [ew prec. data] | 91.2 | $0.1193 \pm 0.0028$ | $0.1182 \pm 0.0010$ | 0.4 |
| → | $e^+e^-$ [jets & shps] | 91 - 208 | $0.1208 \pm 0.0038$ | $0.1182 \pm 0.0011$ | 0.7 |
| → | $e^+e^-$ [5-jet] | 91 - 208 | $0.1155^{+0.0041}_{-0.0034}$ | $0.1183 \pm 0.0010$ | 0.6 |

# $\alpha_s$ in year 2011

2009 world summary

$\alpha_s = 0.1184 \pm 0.0007$




dedicated workshop in Munich in February 2011
1110.0016

Preliminary 2011 average: $\alpha_s = 0.1183 \pm 0.0010$

| | Process | Q [GeV] | $\alpha_s(M_{Z^0})$ | excl. mean $\alpha_s(M_{Z^0})$ | std. dev. |
|---|---|---|---|---|---|
| | $\tau$-decays | 1.78 | $0.1197 \pm 0.0016$ | $0.1180 \pm 0.0011$ | 0.9 |
| | DIS [$F_2$] | 2 - 170 | $0.1142 \pm 0.0023$ | $0.1186 \pm 0.0013$ | 1.7 |
| | DIS [e-p $\rightarrow$ jets] | 6 - 100 | $0.1198 \pm 0.0032$ | $0.1182 \pm 0.0010$ | 0.5 |
| | Lattice QCD | 7.5 | $0.1183 \pm 0.0008$ | $0.1182 \pm 0.0017$ | 0.1 |
| | $\Upsilon$ decays | 9.46 | $0.119^{+0.006}_{-0.005}$ | $0.1183 \pm 0.0010$ | 0.1 |
| new | $e^+e^-$ [jets & shps] | 14 - 44 | $0.1172 \pm 0.0051$ | $0.1183 \pm 0.0010$ | 0.2 |
| → | $p\bar{p}$ incl. jets | 50-145 | $0.1161 \pm 0.0045$ | $0.1183 \pm 0.0010$ | 0.4 |
| | $e^+e^-$ [ew prec. data] | 91.2 | $0.1193 \pm 0.0028$ | $0.1182 \pm 0.0010$ | 0.4 |
| → | $e^+e^-$ [jets & shps] | 91 - 208 | $0.1208 \pm 0.0038$ | $0.1182 \pm 0.0011$ | 0.7 |
| → | $e^+e^-$ [5-jet] | 91 - 208 | $0.1155^{+0.0041}_{-0.0034}$ | $0.1183 \pm 0.0010$ | 0.6 |

Open issue: treatment of very accurate outliers e.g.

$\alpha_s = 0.1135 \pm 0.0010$ [SCET, thrust at N$^3$LO]

Abbate et al. 1106.3080

$\alpha_s = 0.1213 \pm 0.0014$ [$\tau$-decays]

Pich 1001.0389

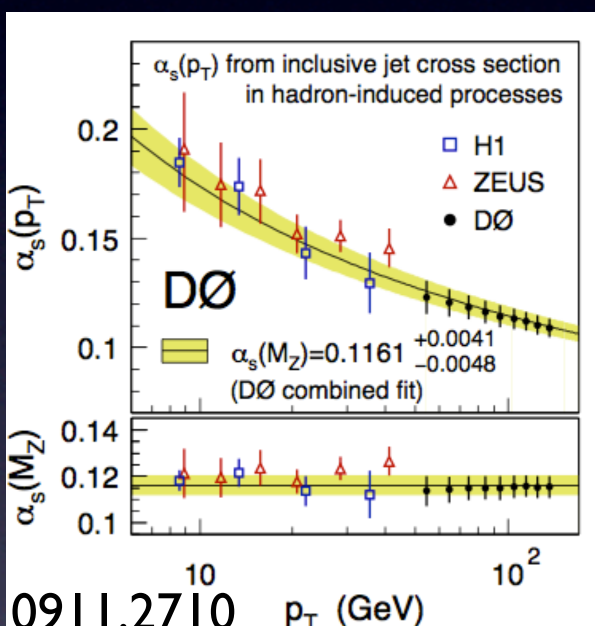
$\alpha_s = 0.1122 \pm 0.0014$ [NNLO DIS]

Alekhin et al. 1001.0389

# $\alpha_s$ in year 2011

dedicated workshop in Munich in February 2011
1110.0016

2009 world summary
$\alpha_s = 0.1184 \pm 0.0007$




**Preliminary 2011 average: $\alpha_s = 0.1183 \pm 0.0010$**

| | Process | Q [GeV] | $\alpha_s(M_{Z^0})$ | excl. mean $\alpha_s(M_{Z^0})$ | std. dev. |
|---|---|---|---|---|---|
| | $\tau$-decays | 1.78 | $0.1197 \pm 0.0016$ | $0.1180 \pm 0.0011$ | 0.9 |
| | DIS $[F_2]$ | 2 - 170 | $0.1142 \pm 0.0023$ | $0.1186 \pm 0.0013$ | 1.7 |
| | DIS [e-p $\to$ jets] | 6 - 100 | $0.1198 \pm 0.0032$ | $0.1182 \pm 0.0010$ | 0.5 |
| | Lattice QCD | 7.5 | $0.1183 \pm 0.0008$ | $0.1182 \pm 0.0017$ | 0.1 |
| | $\Upsilon$ decays | 9.46 | $0.119^{+0.006}_{-0.005}$ | $0.1183 \pm 0.0010$ | 0.1 |
| | $e^+e^-$ [jets & shps] | 14 - 44 | $0.1172 \pm 0.0051$ | $0.1183 \pm 0.0010$ | 0.2 |
| new → | $p\bar{p}$ incl. jets | 50-145 | $0.1161 \pm 0.0045$ | $0.1183 \pm 0.0010$ | 0.4 |
| | $e^+e^-$ [ew prec. data] | 91.2 | $0.1193 \pm 0.0028$ | $0.1182 \pm 0.0010$ | 0.4 |
| → | $e^+e^-$ [jets & shps] | 91 - 208 | $0.1208 \pm 0.0038$ | $0.1182 \pm 0.0011$ | 0.7 |
| → | $e^+e^-$ [5-jet] | 91 - 208 | $0.1155^{+0.0041}_{-0.0034}$ | $0.1183 \pm 0.0010$ | 0.6 |

$$\sigma_{\rm pert} = \left(\sum_n \alpha_s^n c_n\right) \otimes f_1)(\alpha_s) \otimes f_2(\alpha_s)$$

*Competitive measurements at the LHC ? Combined fit with pdfs or use ratios ?*

Open issue: treatment of very accurate outliers e.g.

$\alpha_s = 0.1135 \pm 0.0010$ [SCET, thrust at $N^3LO$]
Abbate et al. 1106.3080

$\alpha_s = 0.1213 \pm 0.0014$ [$\tau$-decays]
Pich 1001.0389

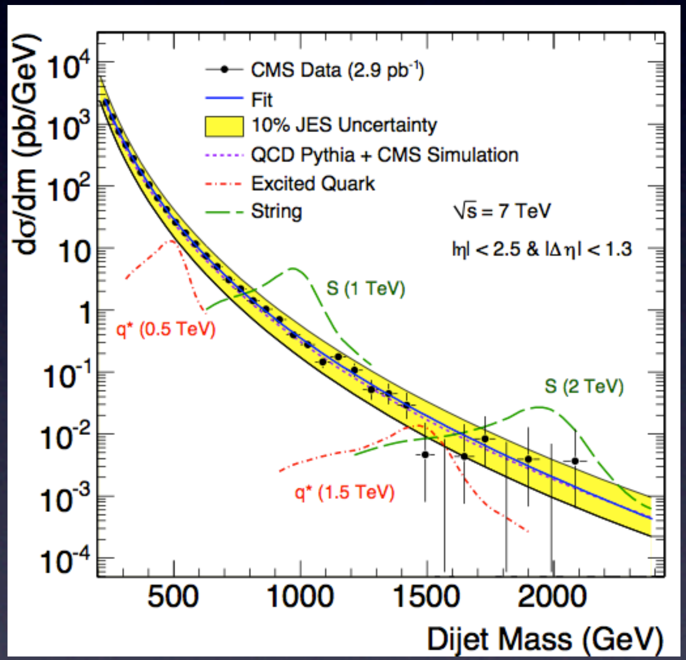
$\alpha_s = 0.1122 \pm 0.0014$ [NNLO DIS]
Alekhin et al. 1001.0389

# Jet algorithms

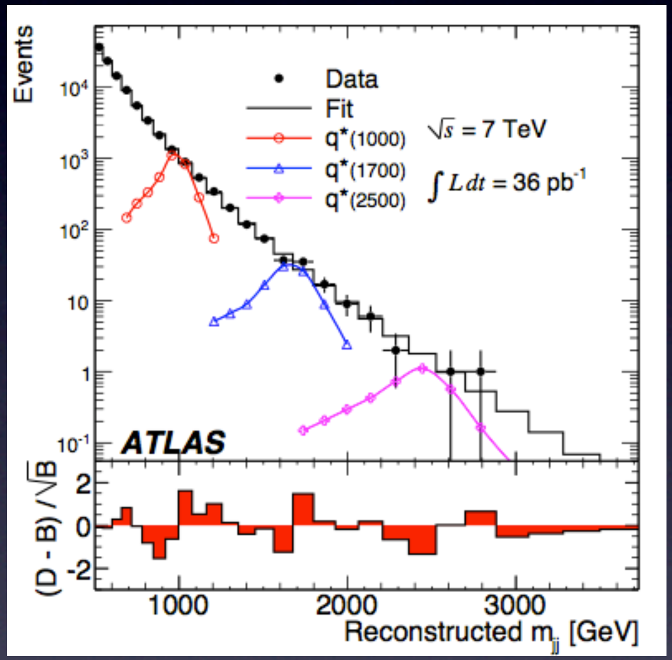

ATLAS and CMS adopted as default jet-algorithm: anti-$k_t$

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

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
~ 4 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

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

# Inside jets

Today, we have a yet more sophisticated description 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 recluster it and veto asymmetric wide angle recombinations
  - trimming: discard regions in a jet with too little energy

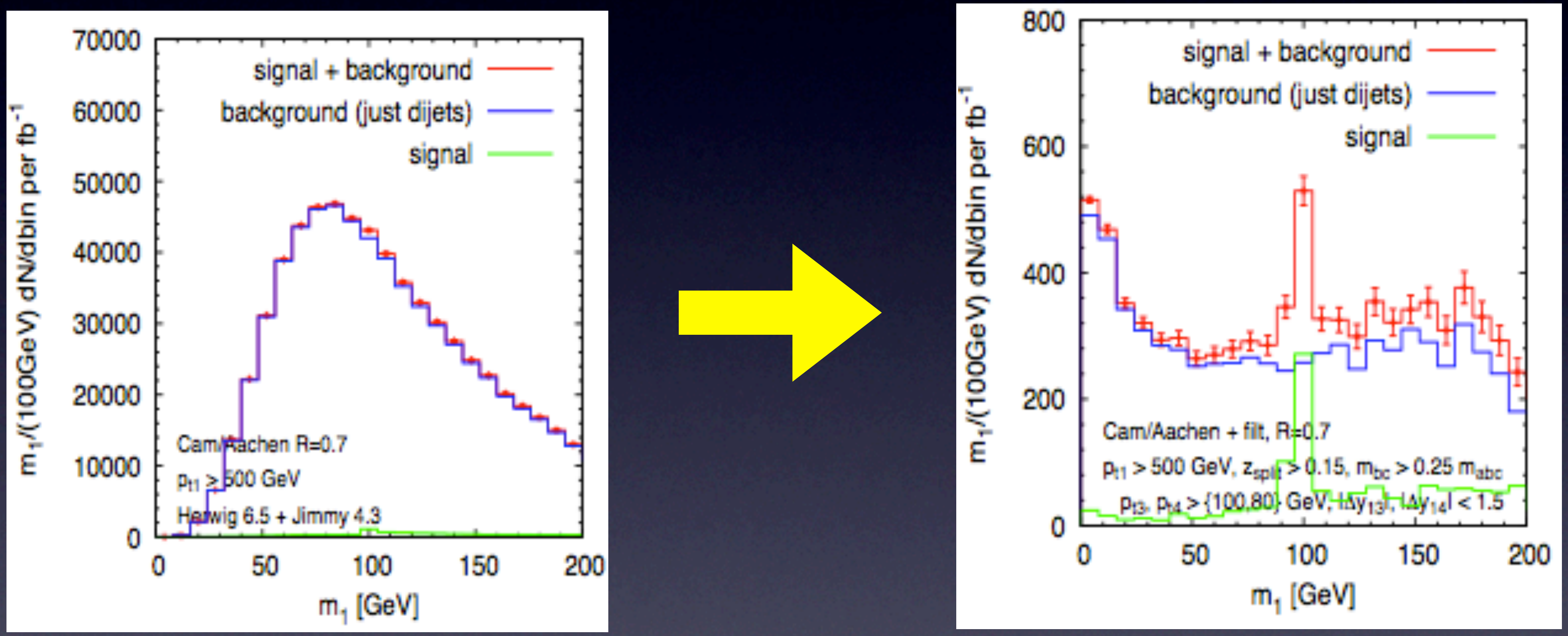
\+ big gain in sensitivity over traditional methods

− might lose many events with boosted regime and kinematical cuts

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, 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"

# Jets in SUSY

New methods already in use at the LHC

Example relevant for WH(→bb):
single jet hadronic mass in W+1j

Z peak evident. Very promising

Expect many new results with boosted techniques at higher statistics soon

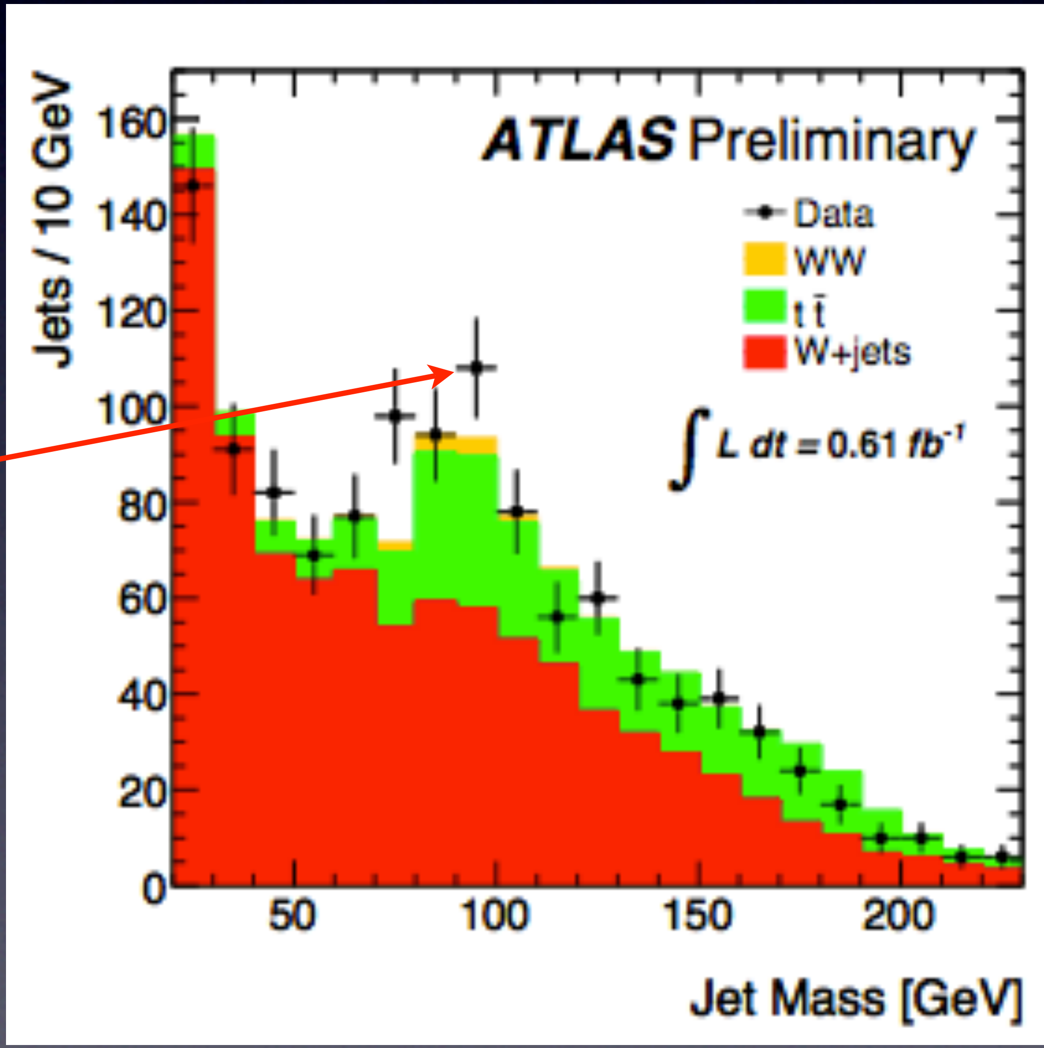



Figure taken from talk given by Ricardo Goncalo on behalf of the ATLAS collaboration at EPS 2011

# Conclusions

SM/QCD is a very dynamic field. Enormous progress in recent years

- 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, ...]
- ...

Spectacular results obtained at the LHC using the most advanced QCD Tools (e.g. SM Higgs already cornered). But there is still lots more to come out of the LHC. We are well prepared to get the most out of it.