Standard Model theory for collider processes

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Europhysics Conference on High Energy Physics

A conference on Particles and the Universe

Open questions

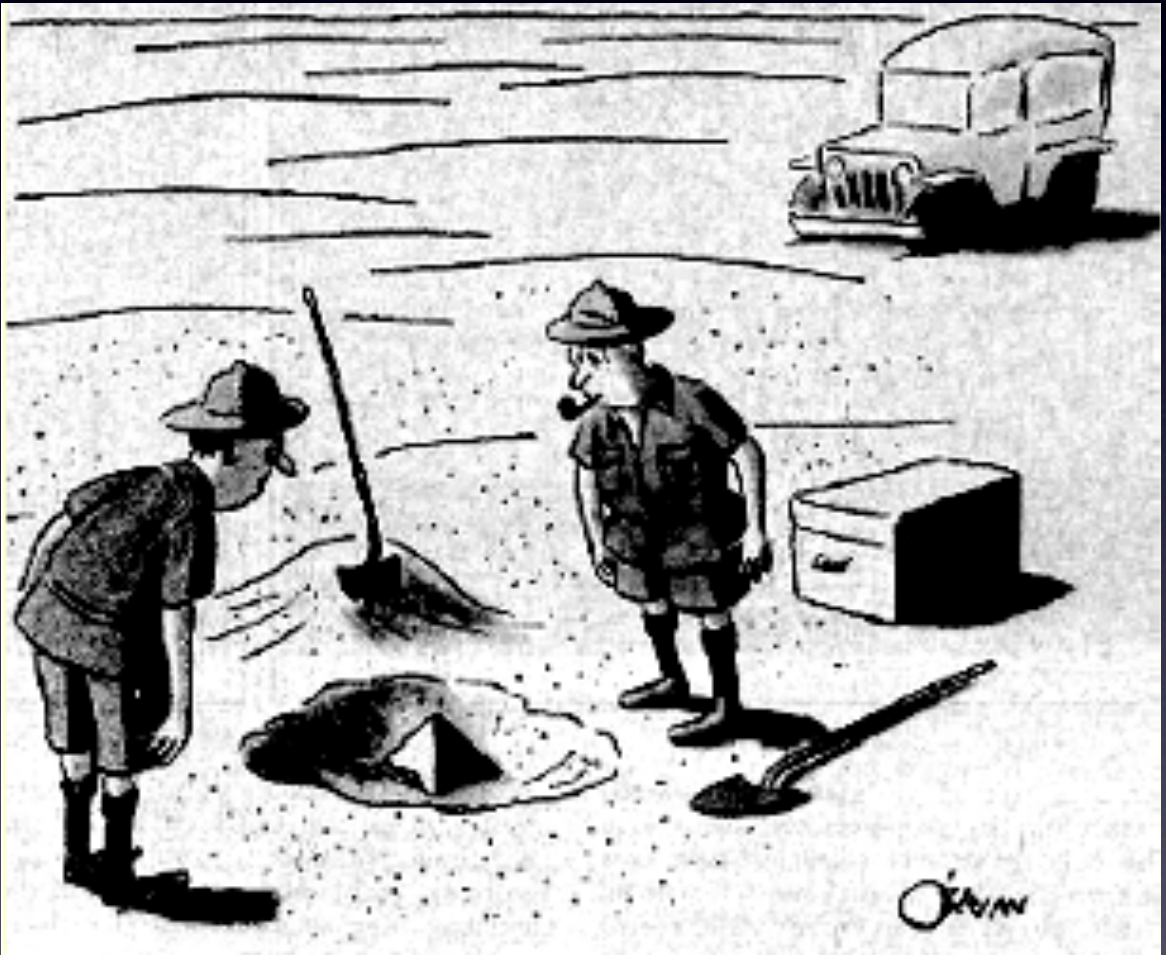
Today, we face many open questions some driven by experimental data (they have an answer), most driven by theoretical curiosity and ambition (they might have an answer)

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"

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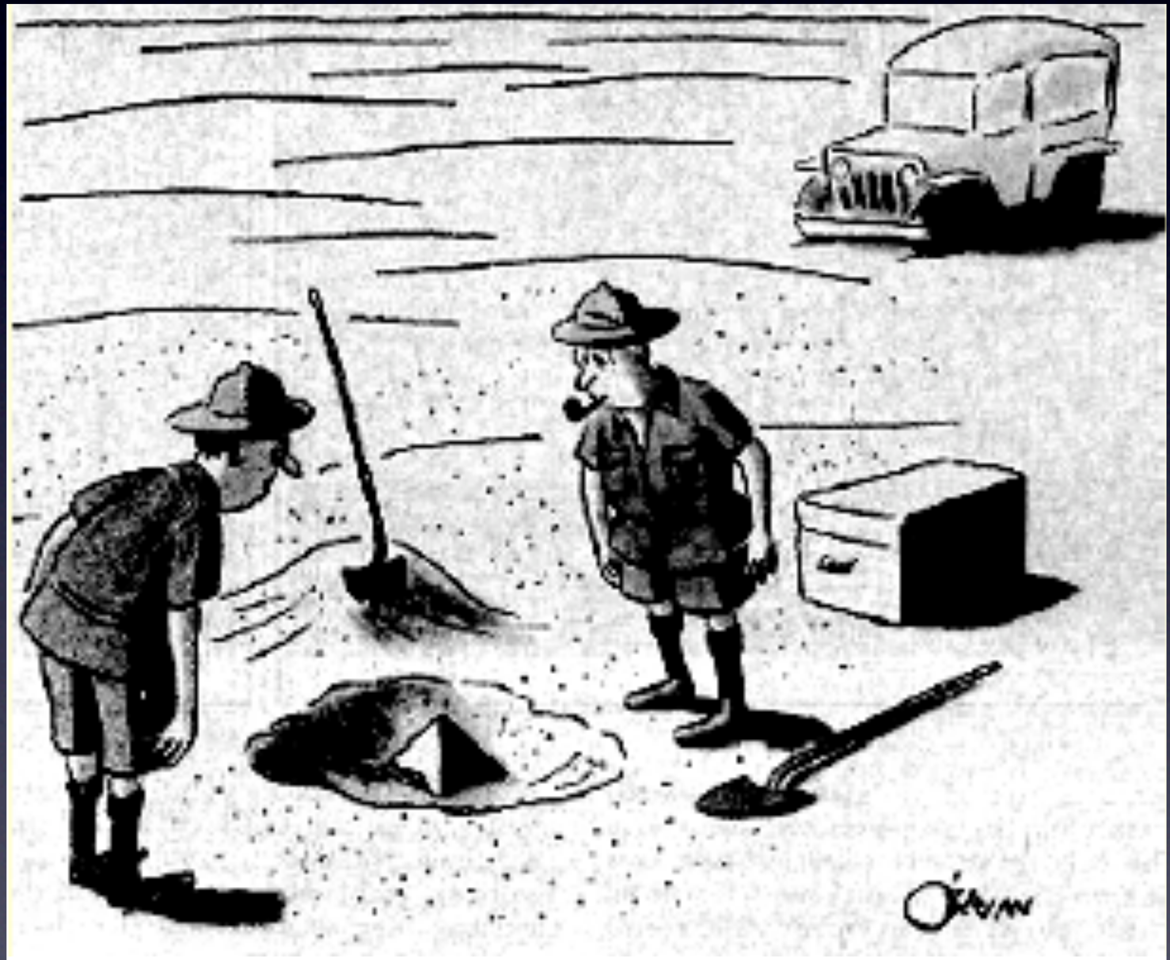
LHC & the big questions

- 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



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LHC status

2010 data: ~45pb^{-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 [July]: >1 fb^{-1}

- O(100) presentations here from ATLAS and CMS, most of them with O(0.2-0.9) fb^{-1} [~60 ATLAS, ~50 CMS] given here
- searches with sensitivities already exceeding those of LEP and Tevatron

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

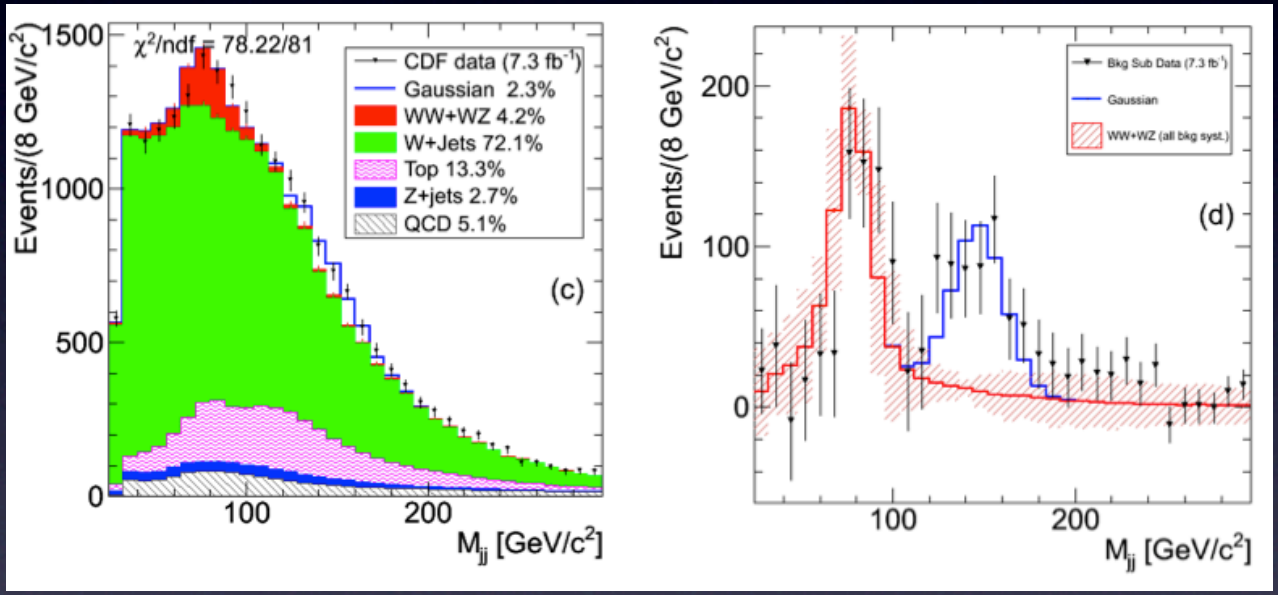
The 2010 - 2011 run was much more successful than any theorist expected!

Meanwhile in Batavia

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

1104.0699

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



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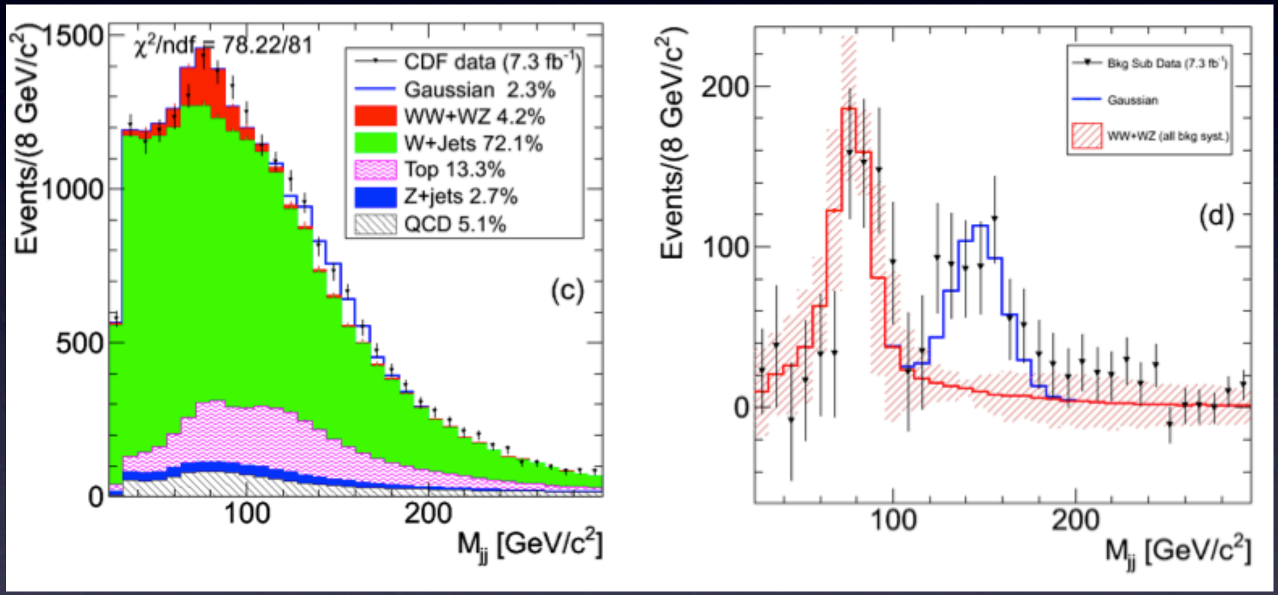

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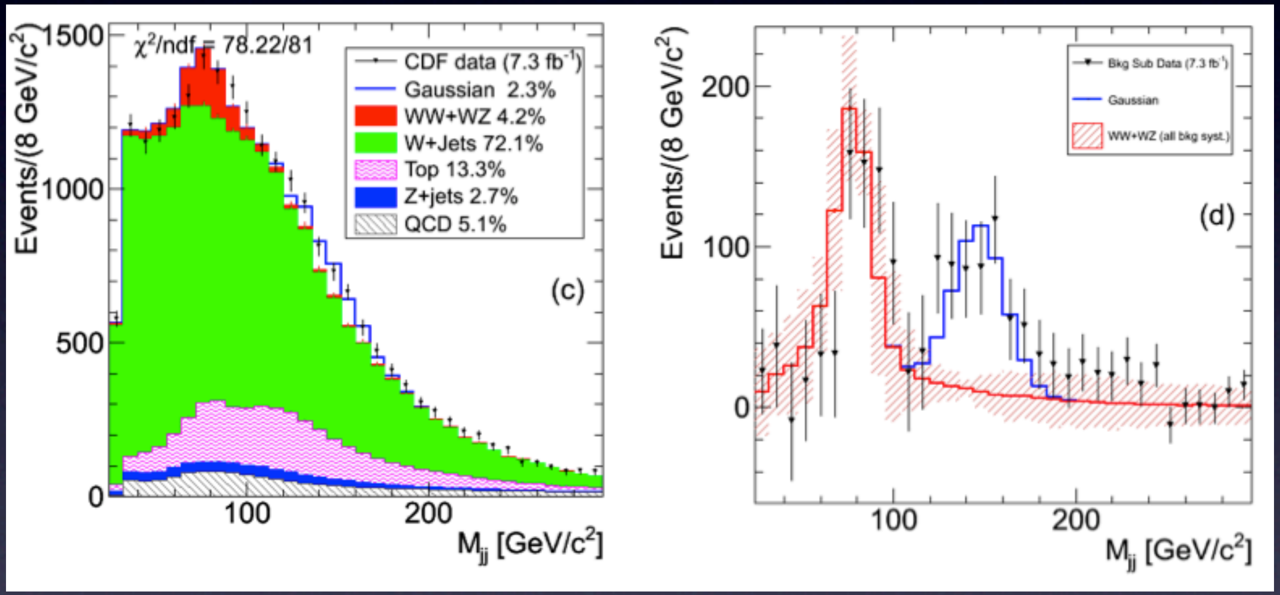

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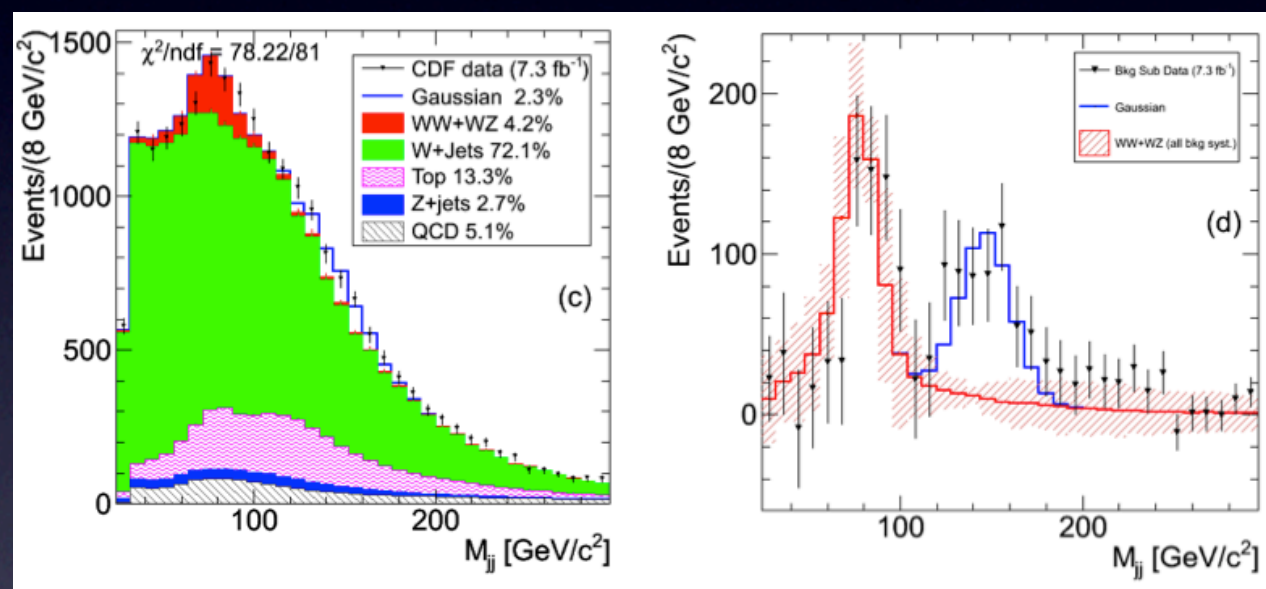

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- D0 data do *not* support excess seen by CDF D0 col. 1106.1921

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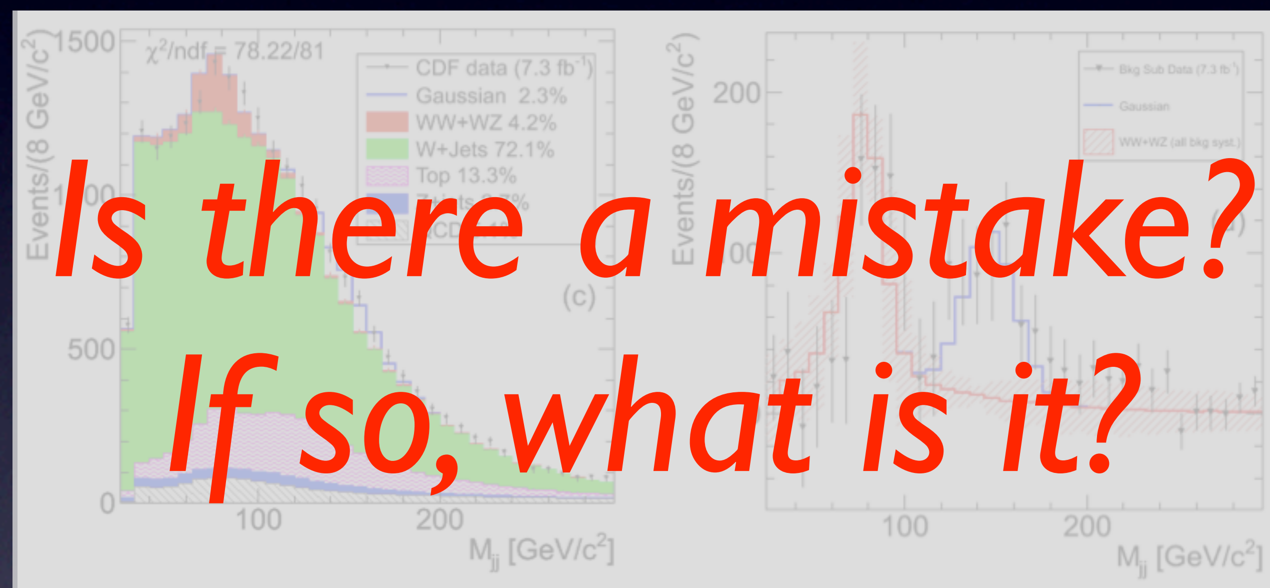

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Other current few σ:

$B_s \to \mu^+\mu^-$ [CDF], dimuon charge asymmetry [D0], W+b [CDF], tt asymmetry [CDF, D0], $(g-2)_\mu$ . . .

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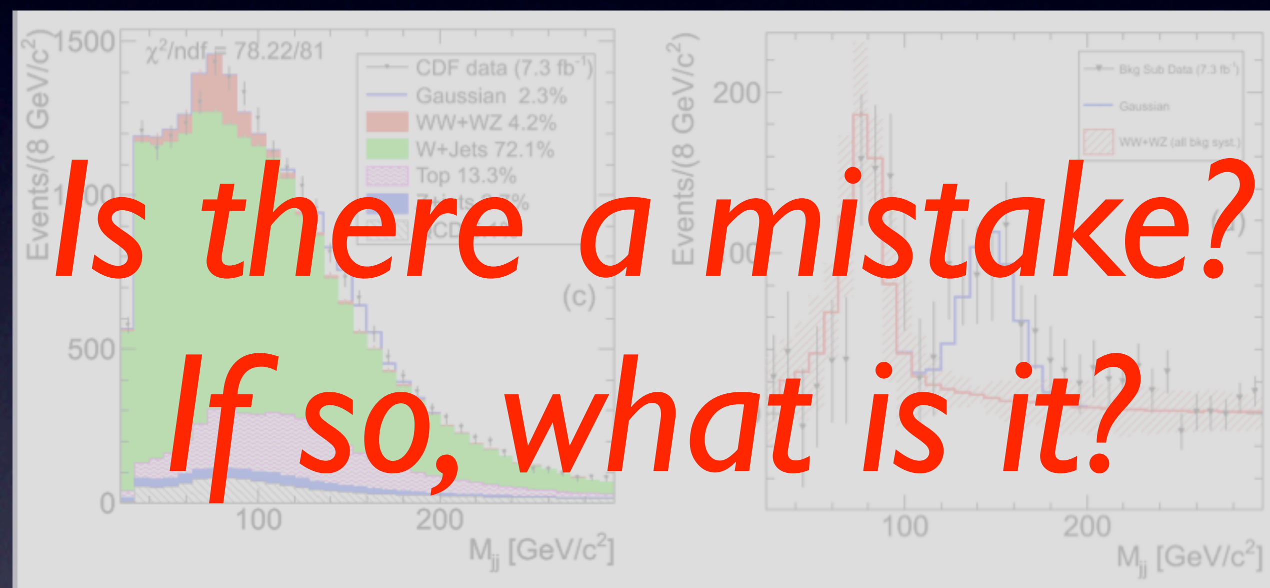

Is there a mistake?

If so, what is it?

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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, MCFM, NLOjet++, Samurai, Rocket, VecBos ...]
- NLO+ PS [(a)MC@NLO and POWHEG]
- NLO + NLL (NNLL) analy. resummations [CAESAR, ResBos + observable specific predictions, sometimes from effective theories]

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

- 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 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 [Madgraph, Sherpa, Alpgen ...]

PS/ME

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 ME (Comix) via CKKW matching
- Madgraph (5.0): automated HELAS routines, more extended spin and color support, increased speed and stability, complex decay chain . . .

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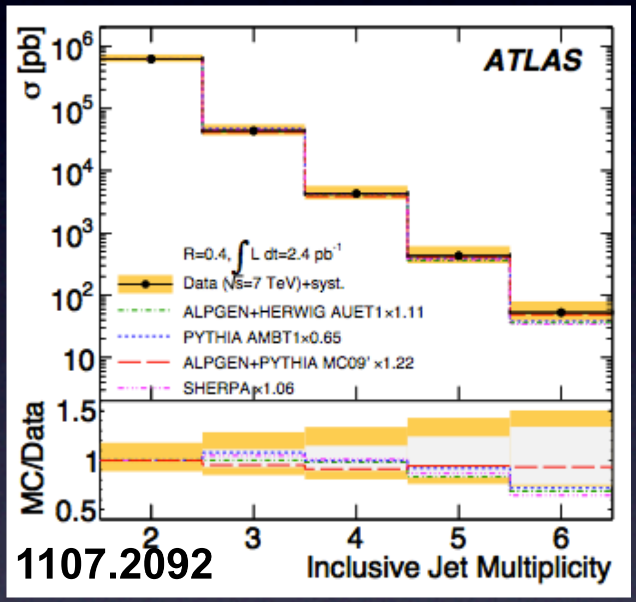
Fast progress in various directions

These codes will undergo continuous stress test in the coming years.

How are they doing right now?

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 . . .)



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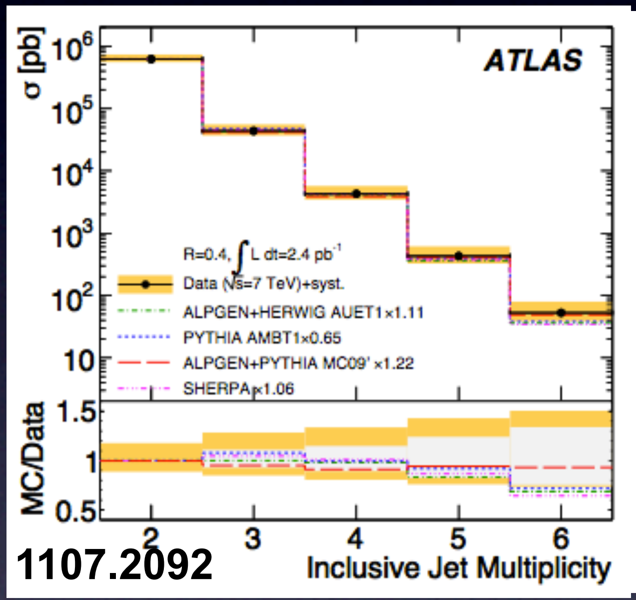

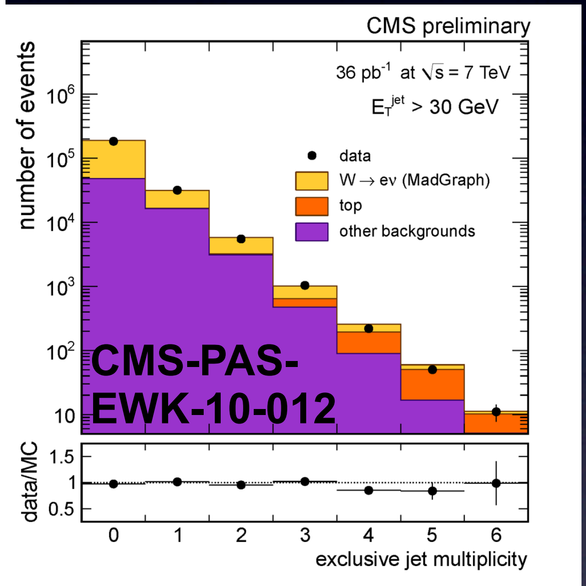

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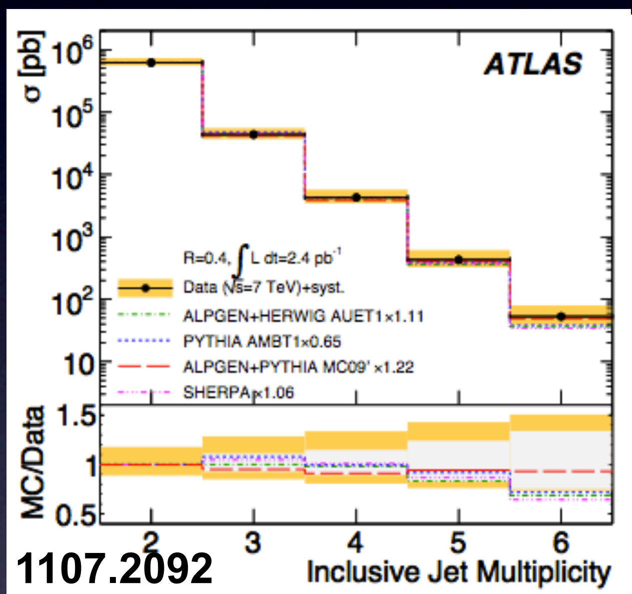

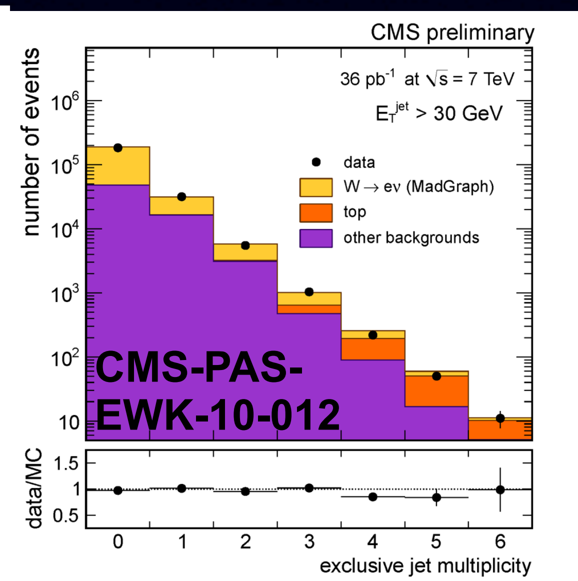

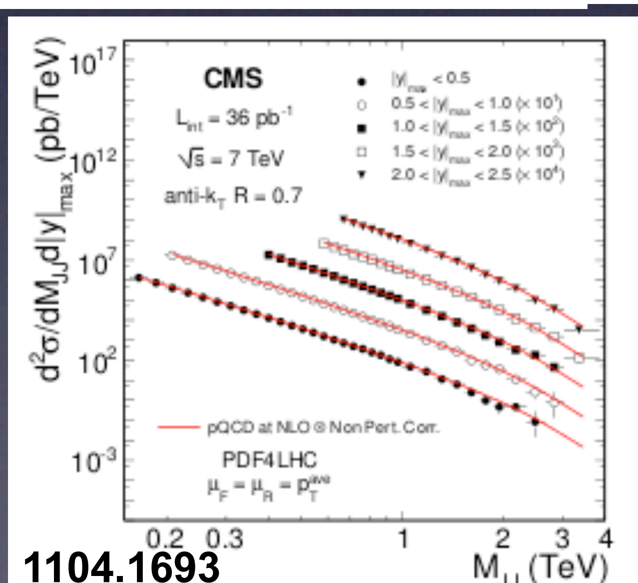

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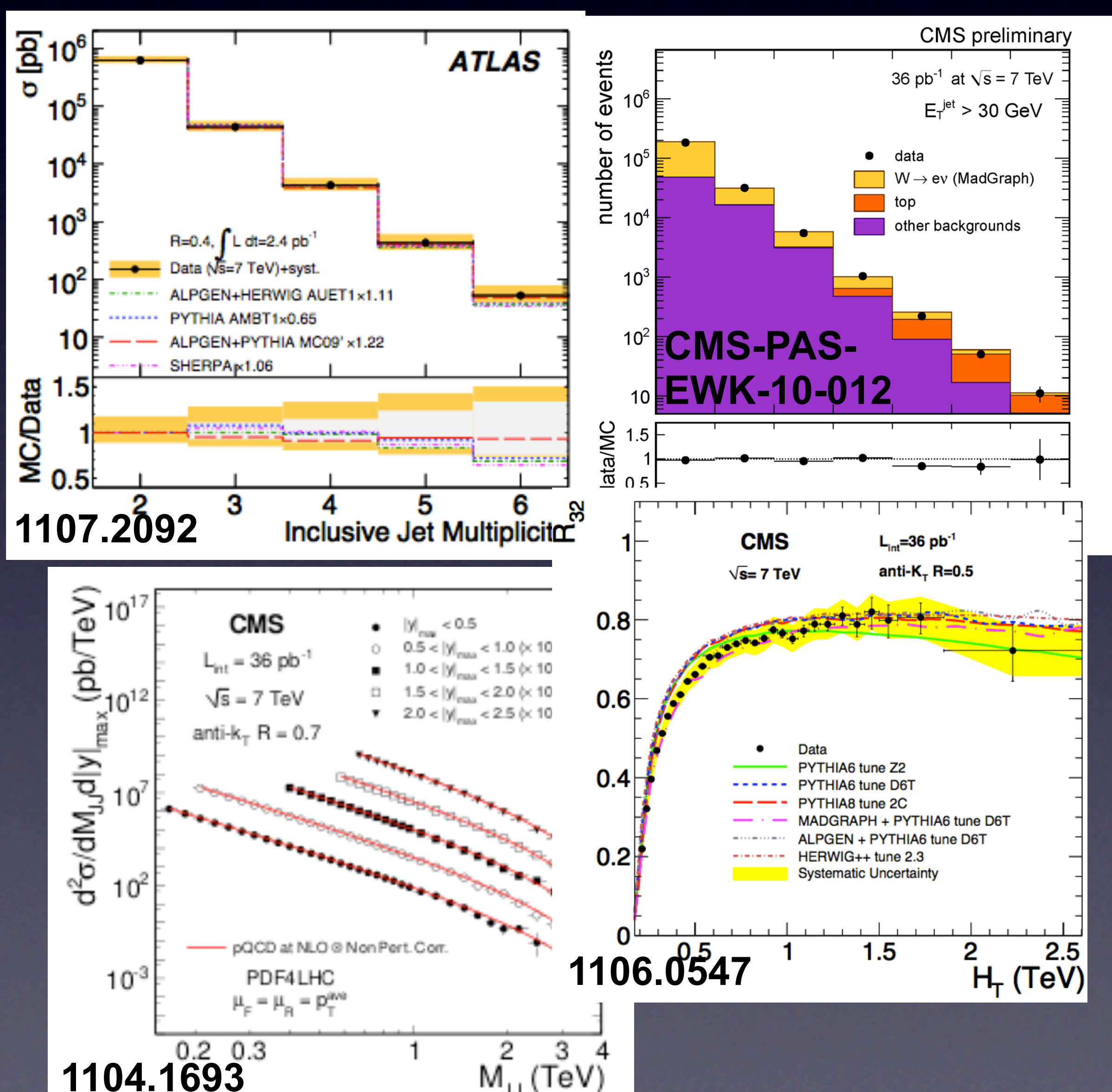

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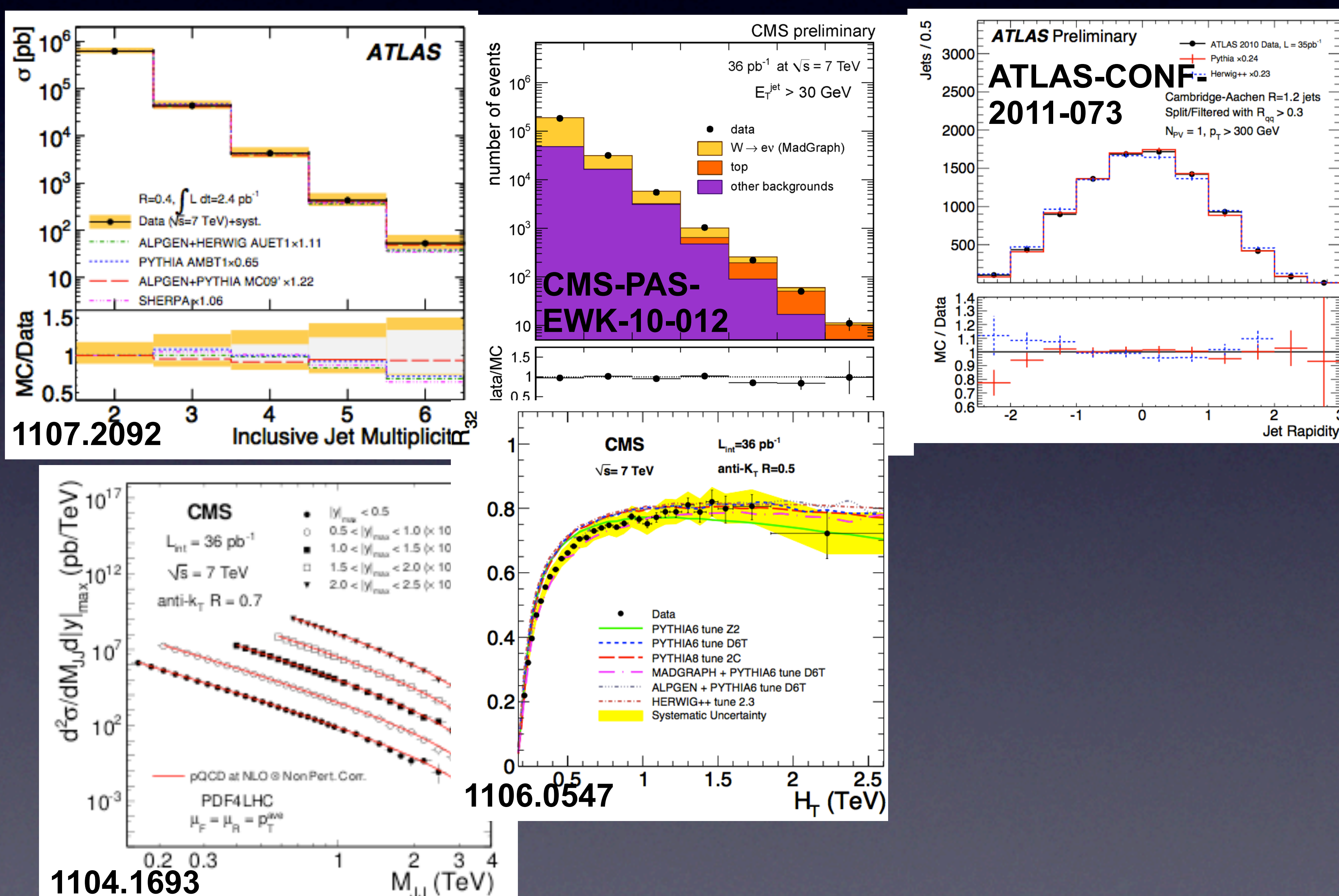

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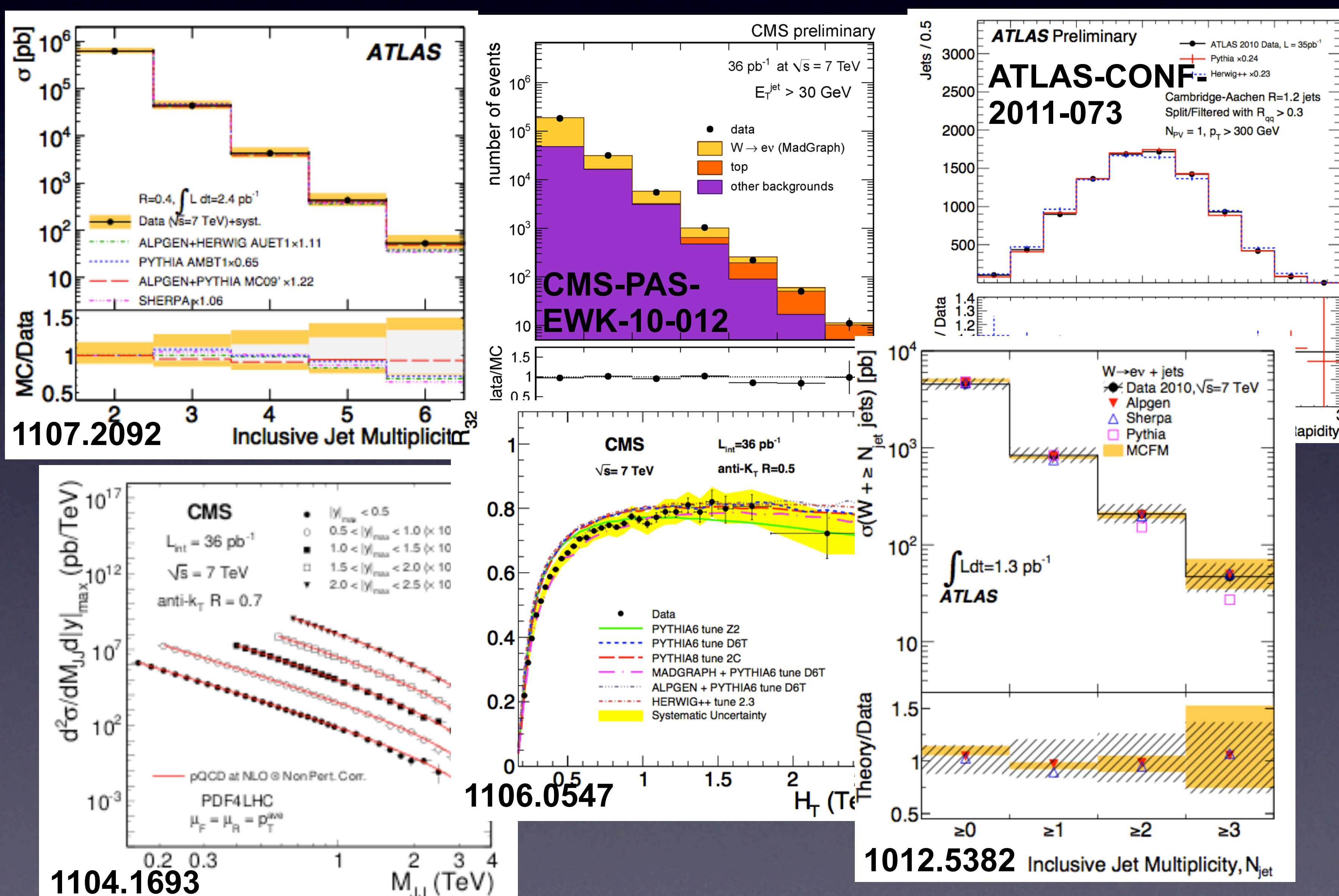

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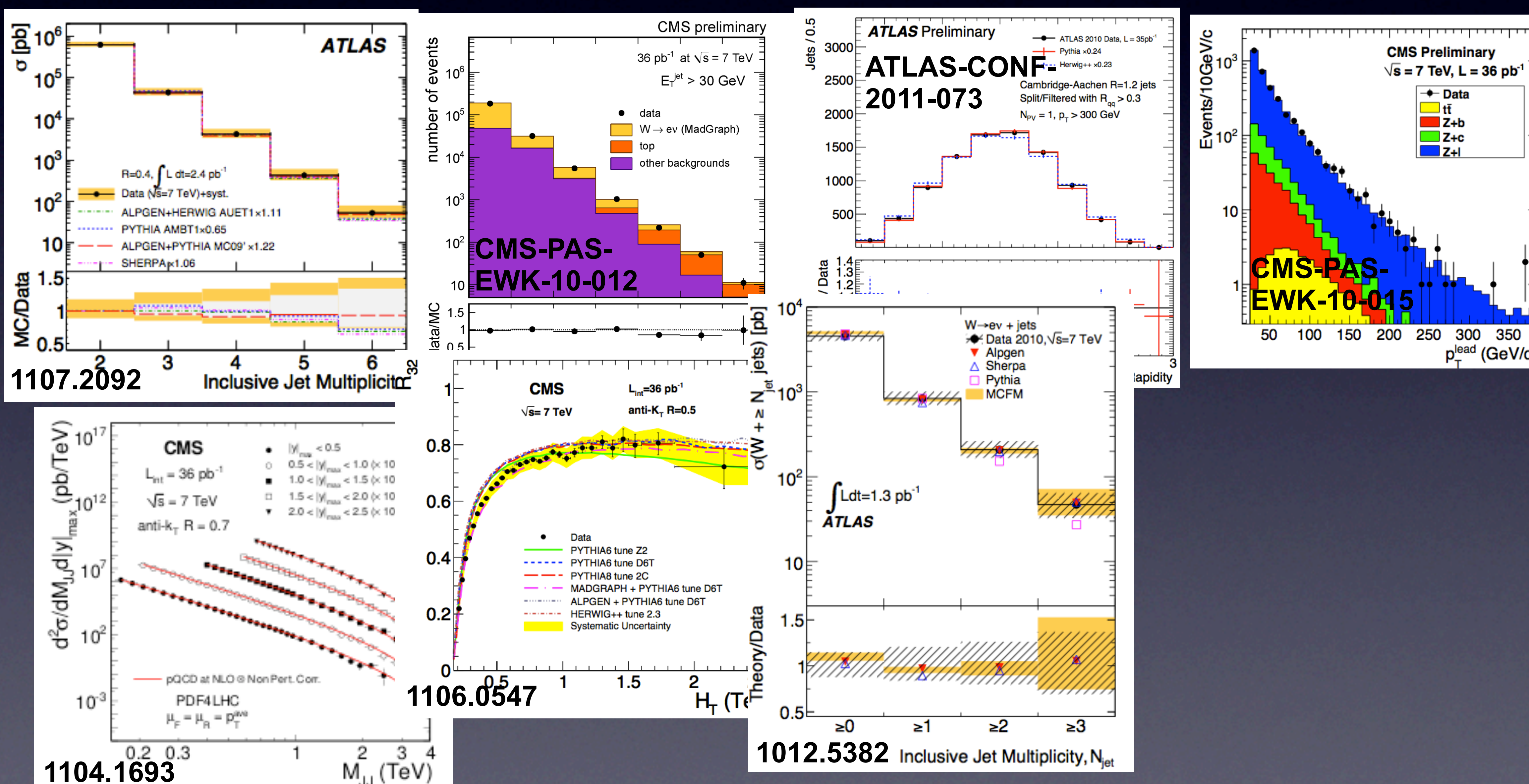

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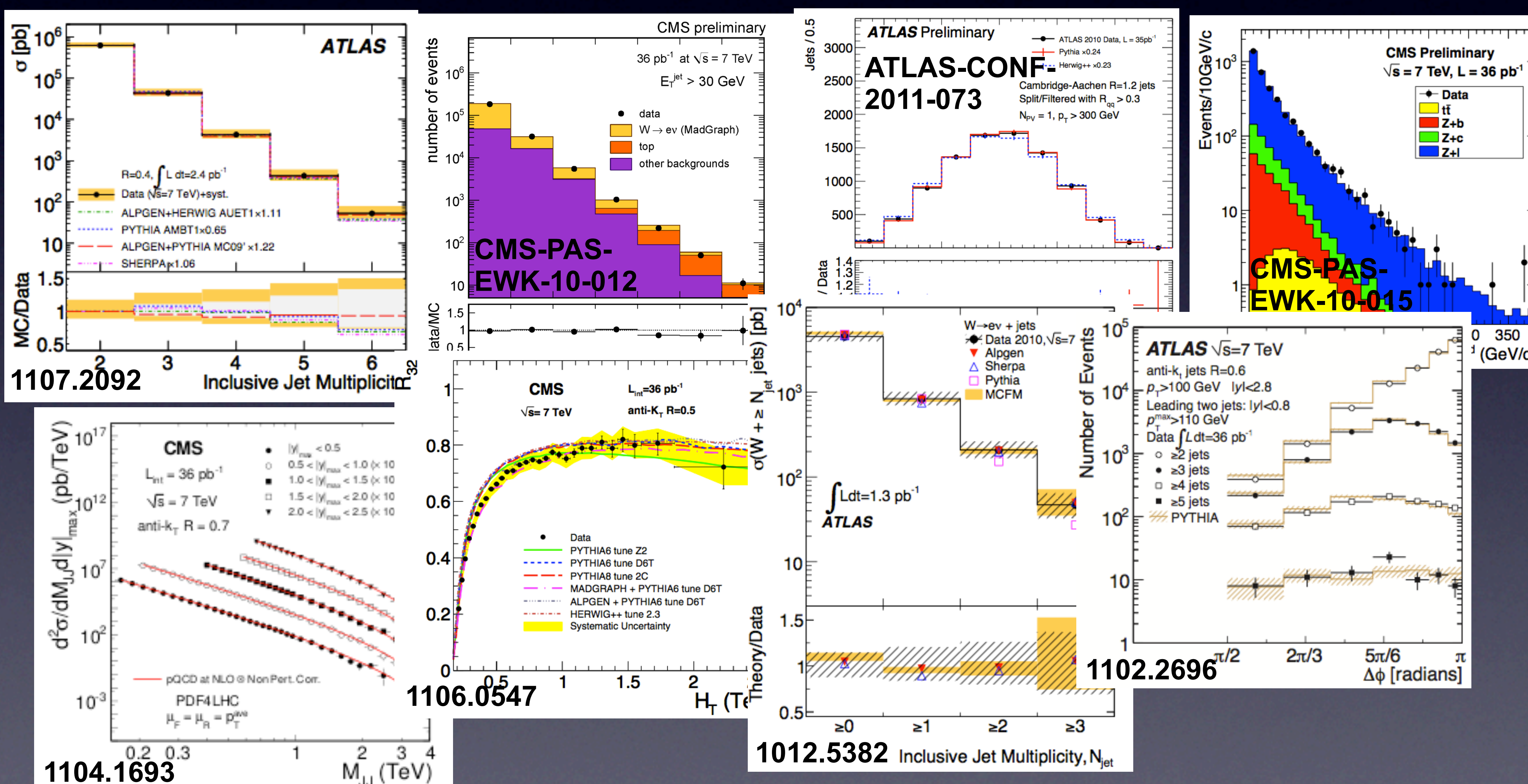

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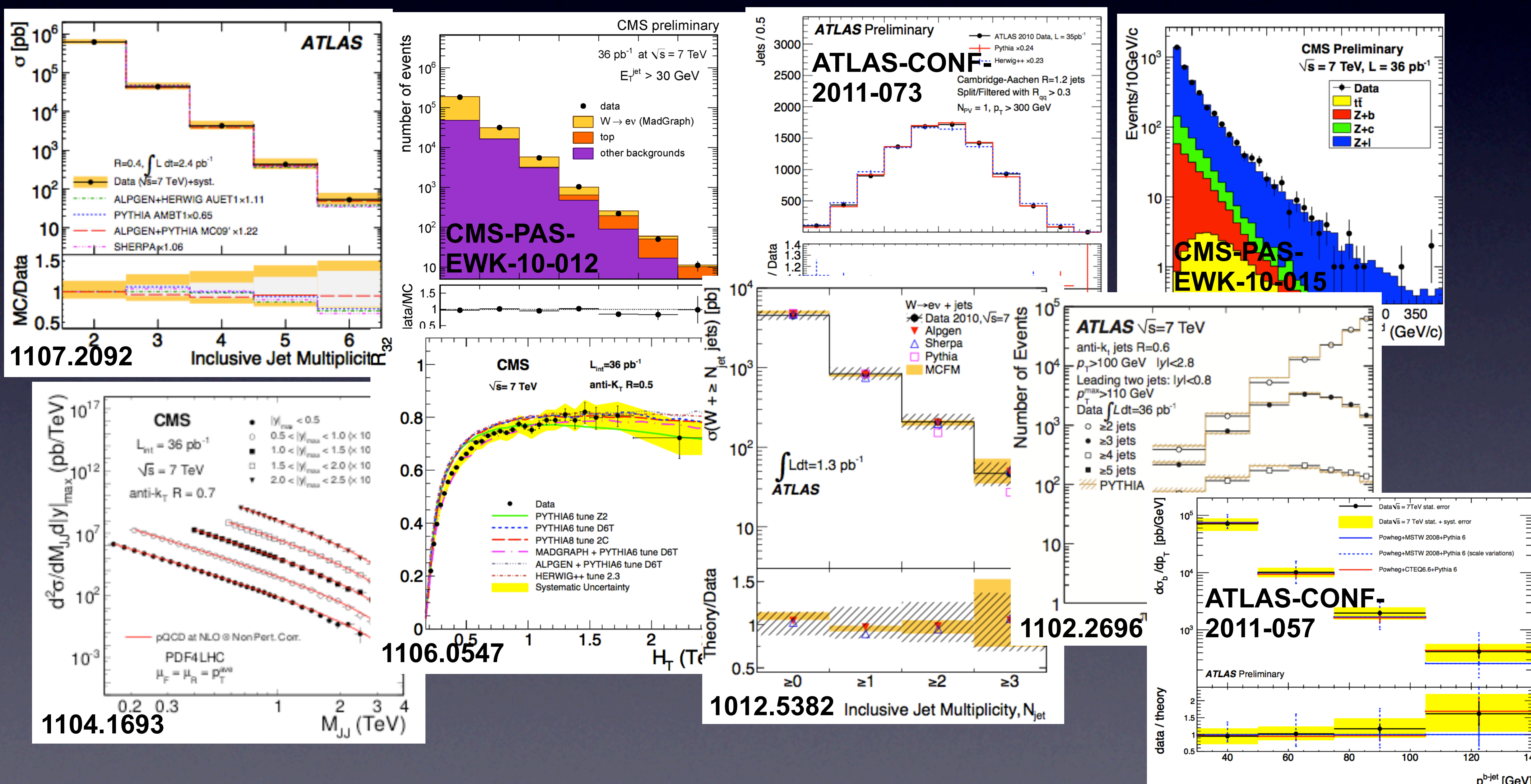

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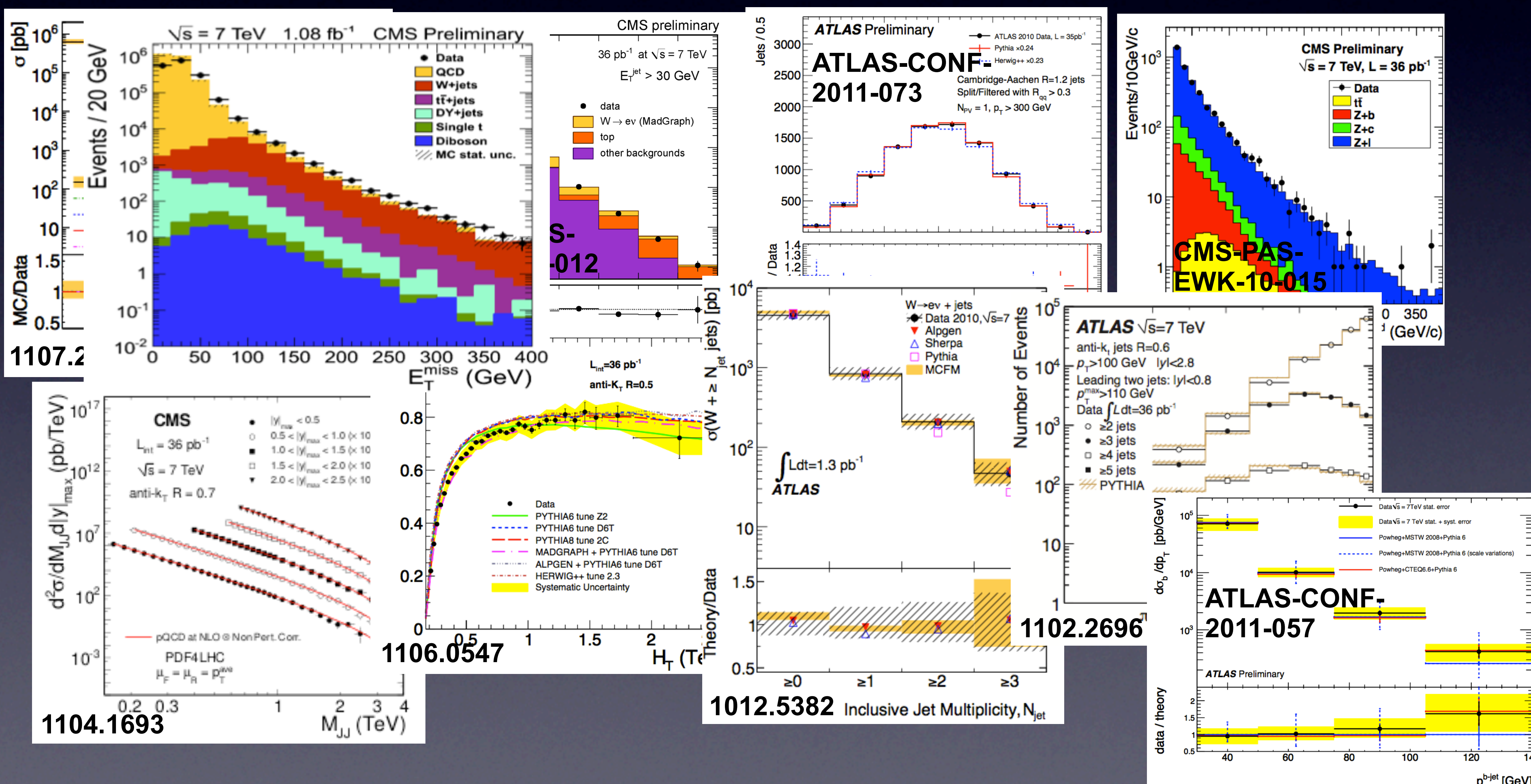

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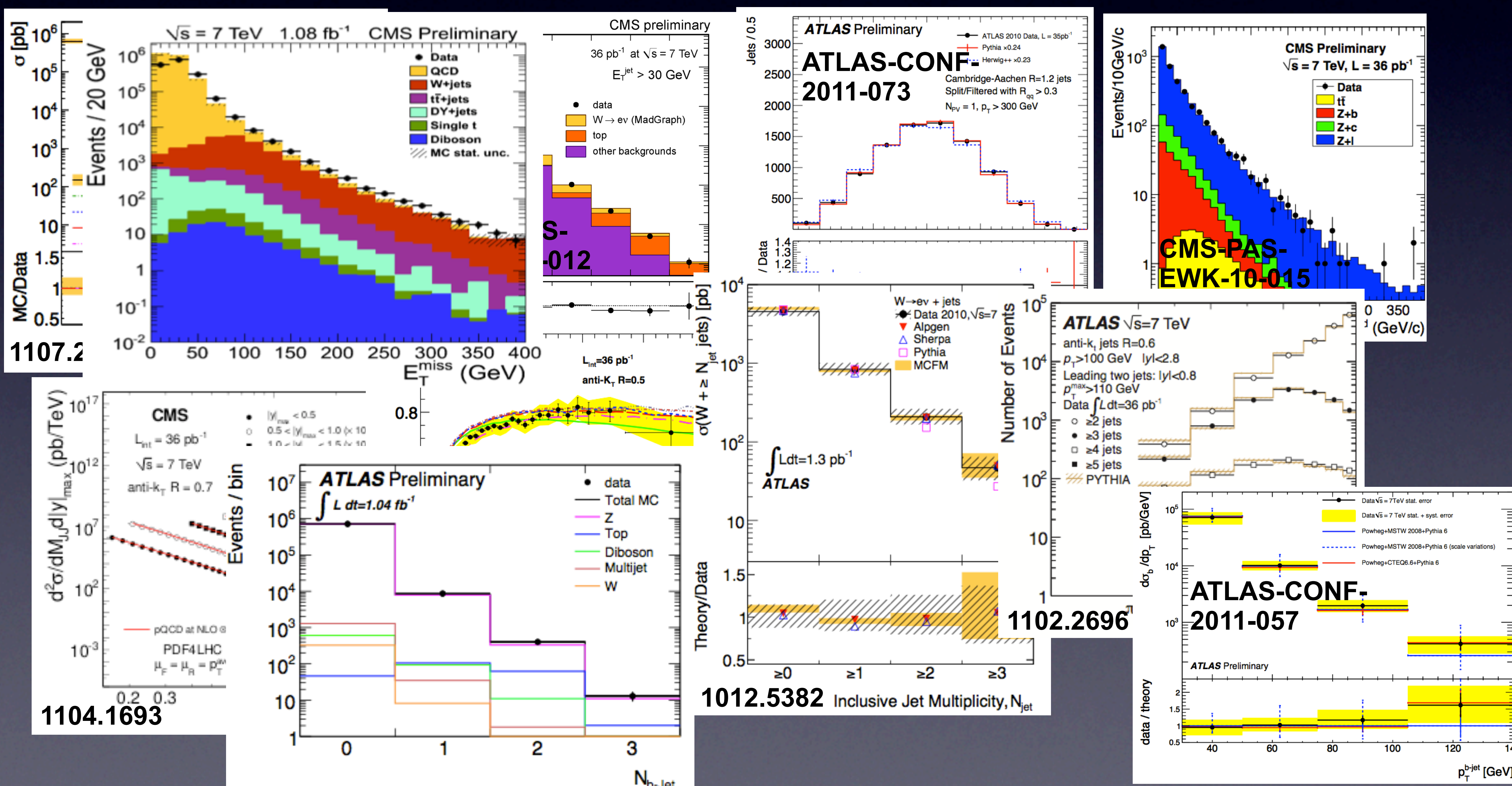

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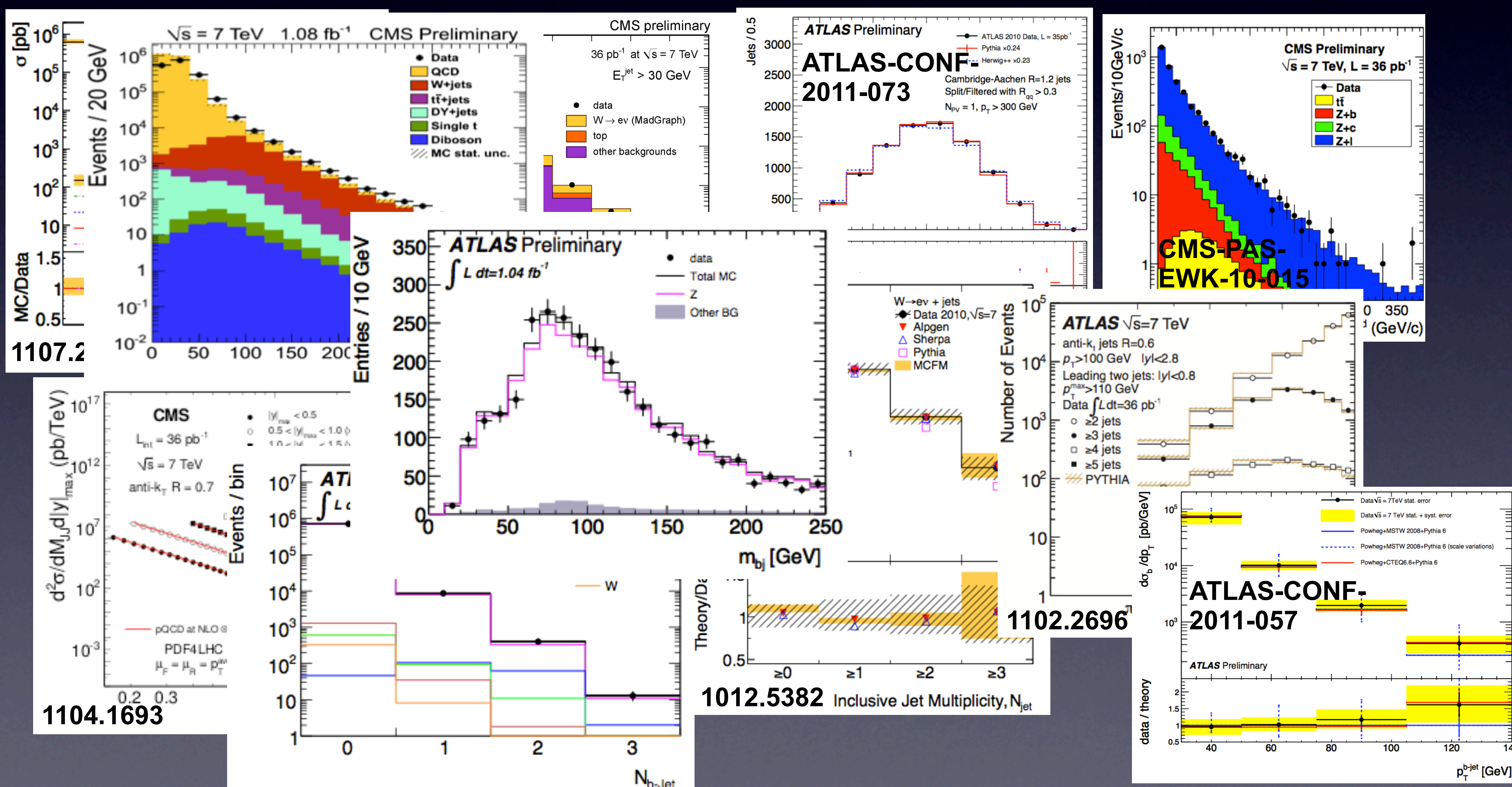

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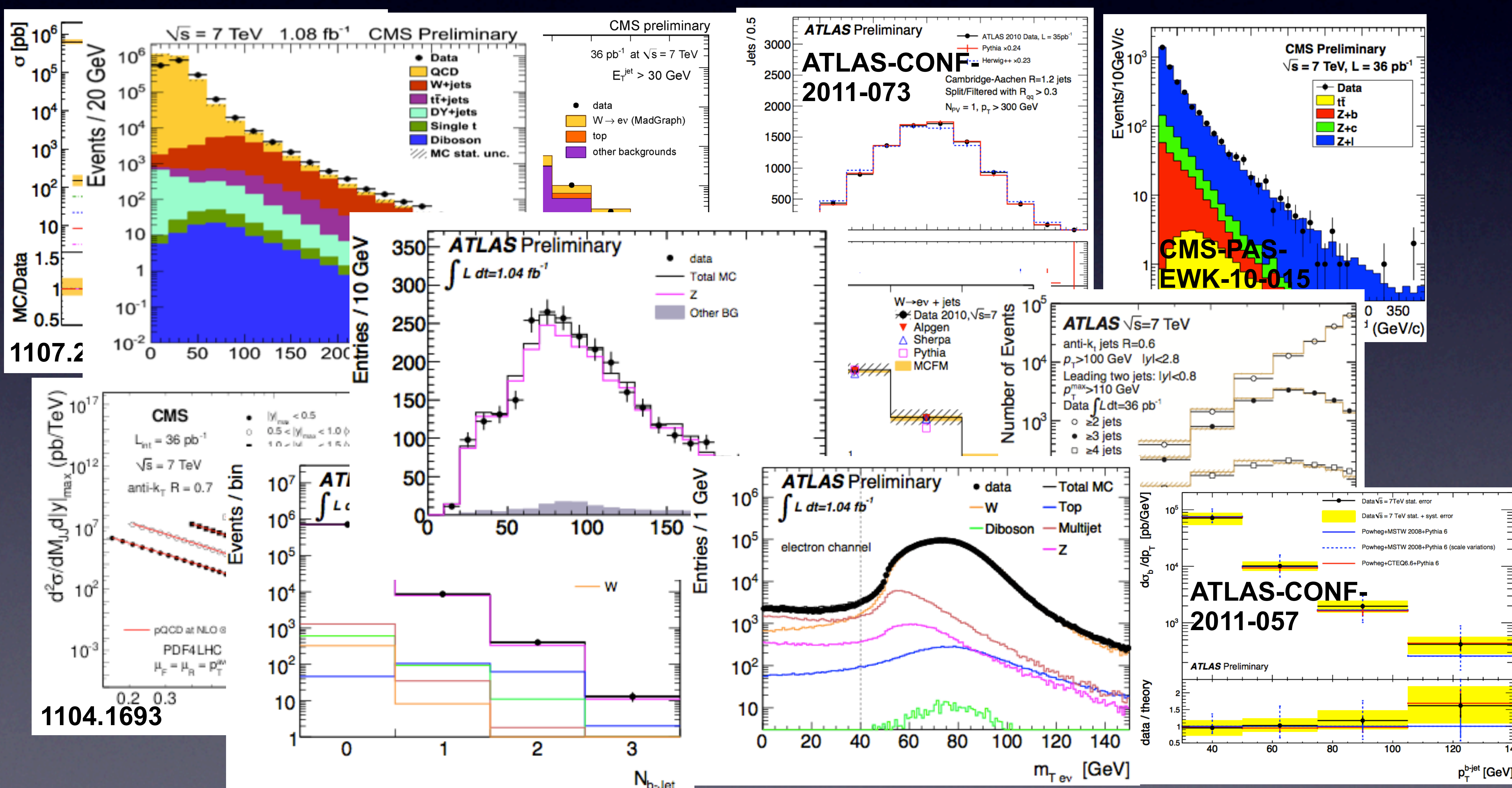

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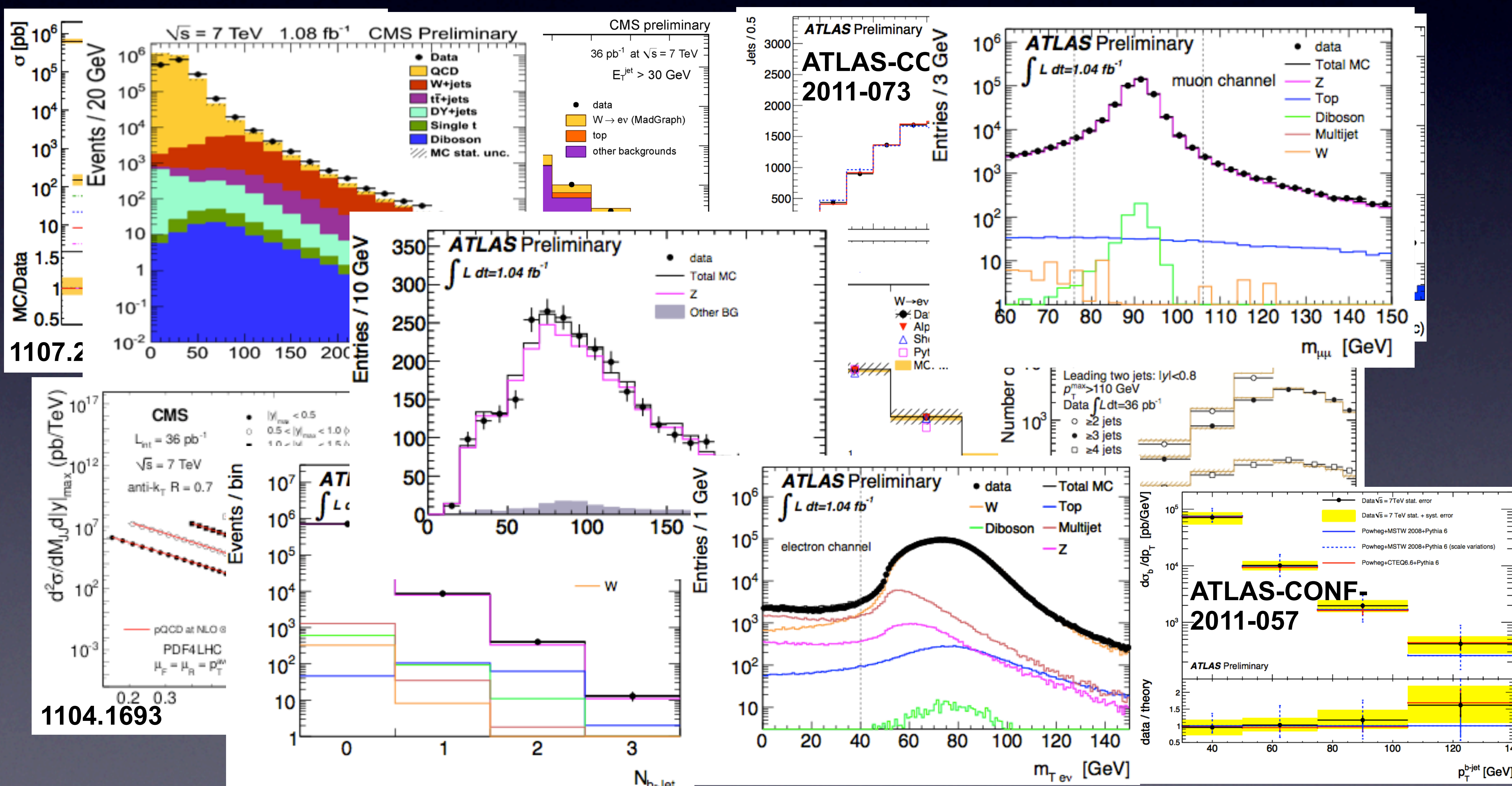

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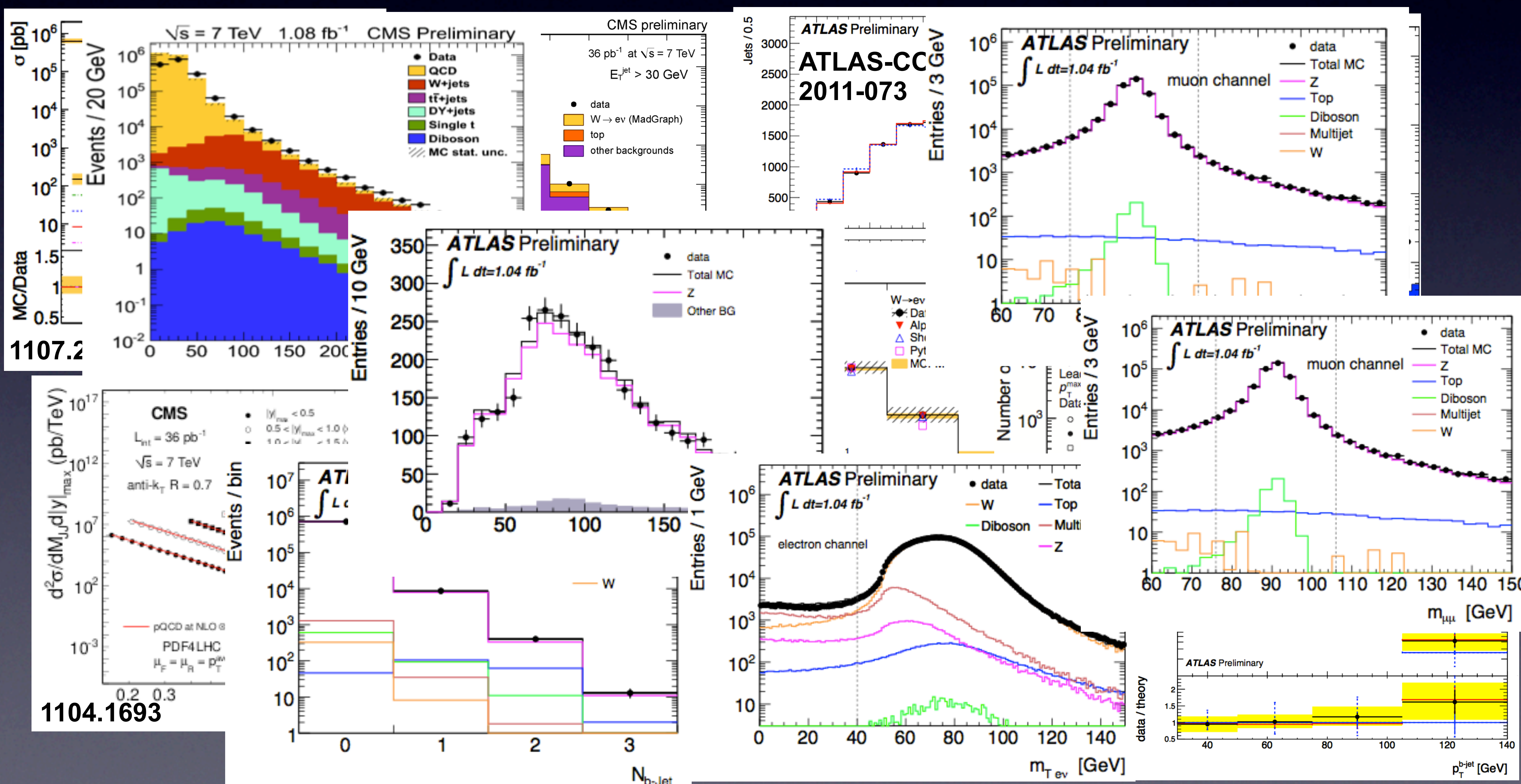

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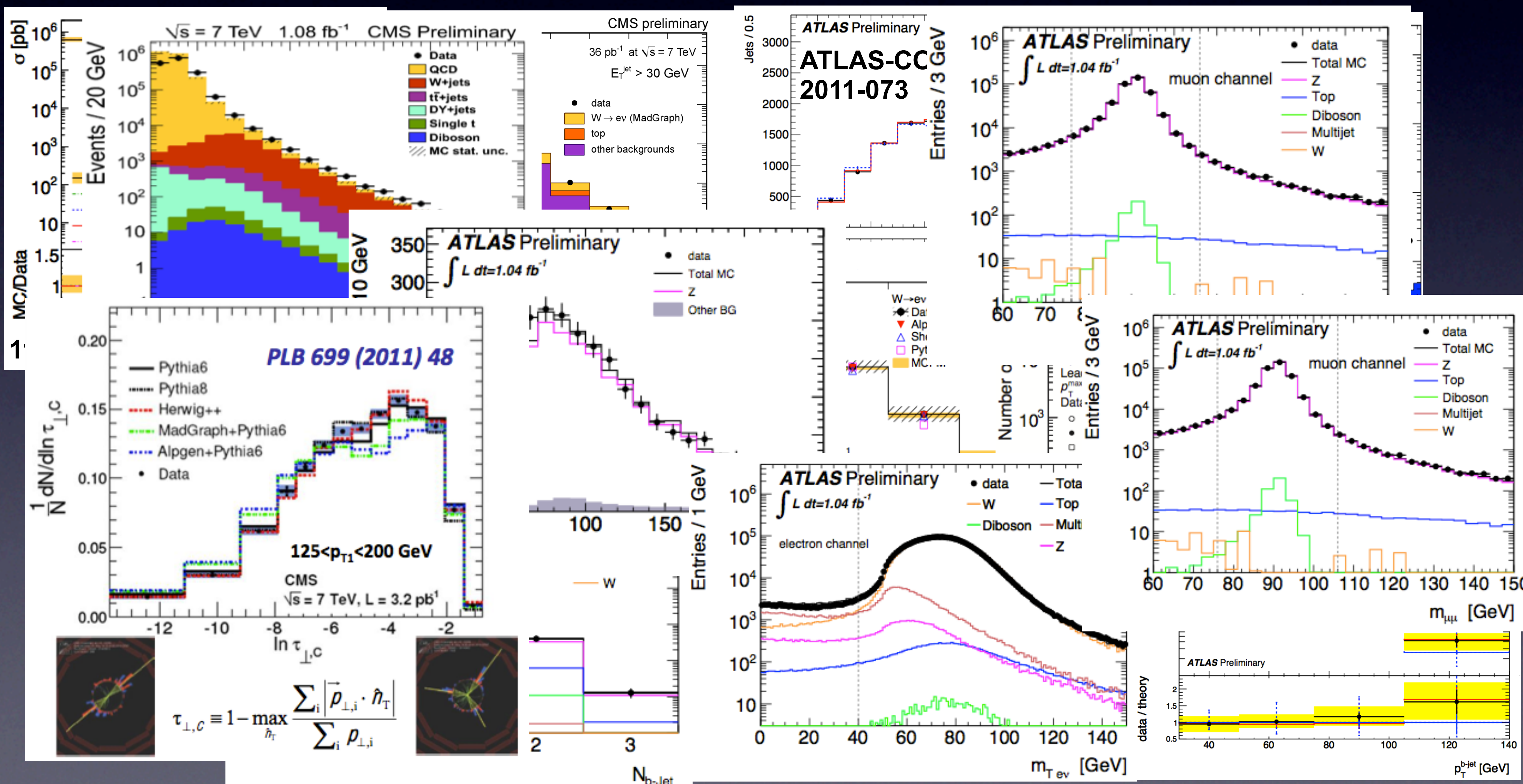

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G. Zanderighi – Oxford University

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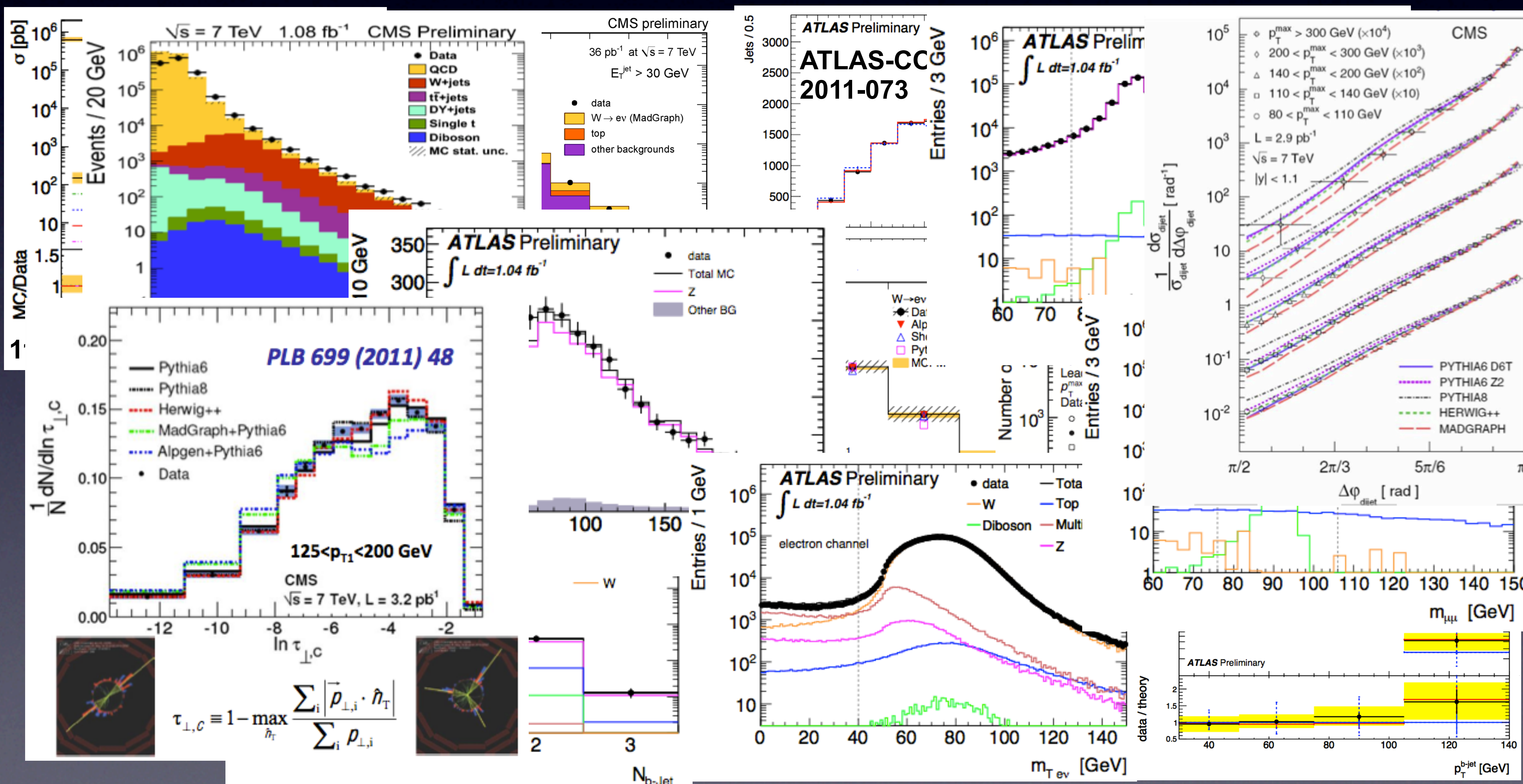

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The NLO revolution

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 ...

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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 ...

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➟ see talk of L. Dixon

Breakthrough 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

The NLO revolution

These 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]

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

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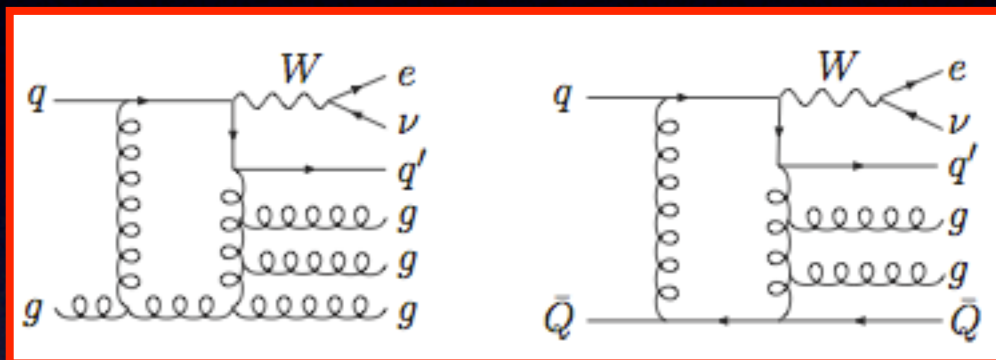
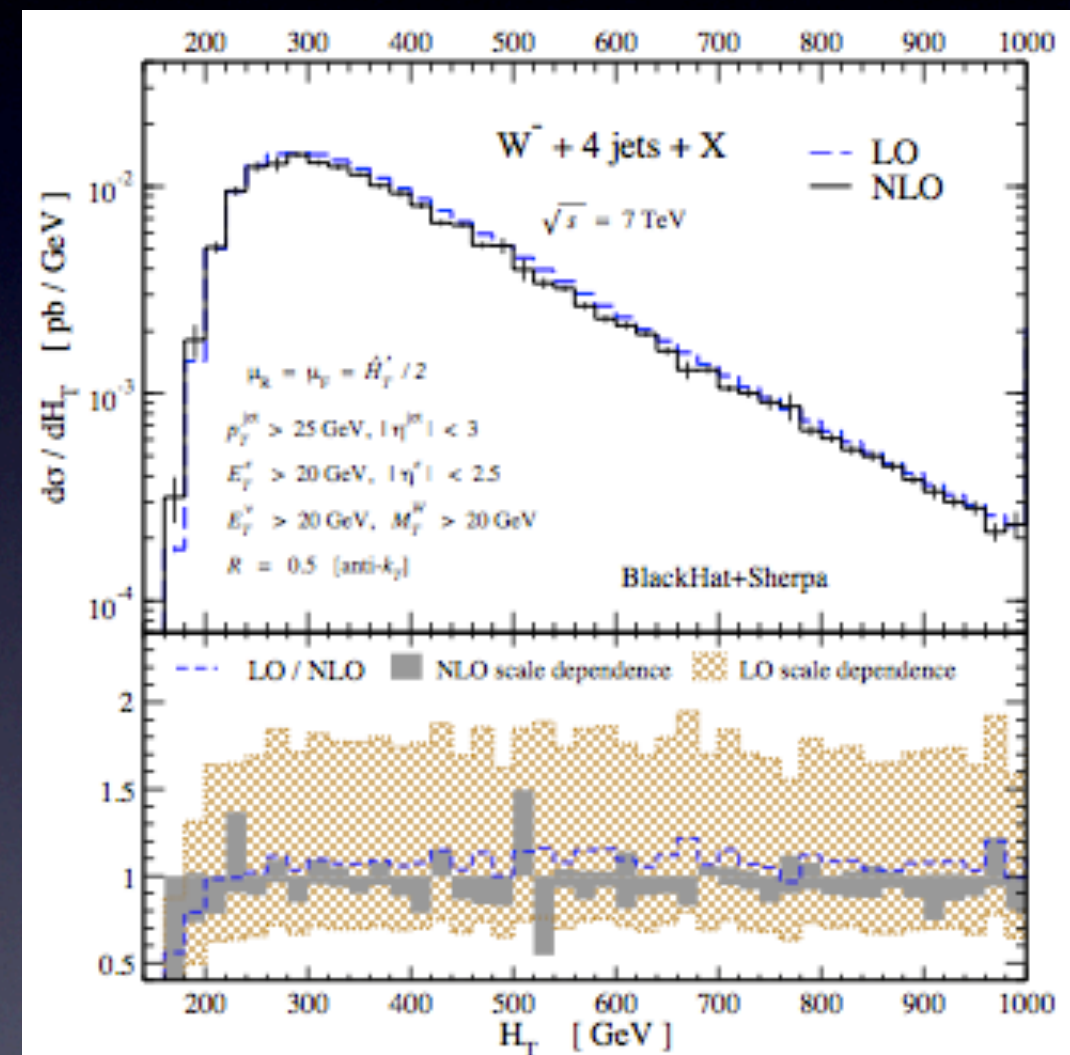
The revolution is not in the applications that we see today, rather in the prospect for low-cost automated NLO calculations even beyond 2 → 4 in the near future

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)

MadLoop

Hirschi et al. 1103.0621

Automation of NLO

- 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?

Very valuable even with these restrictions. Improvements and refinements expected soon.

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

[...]

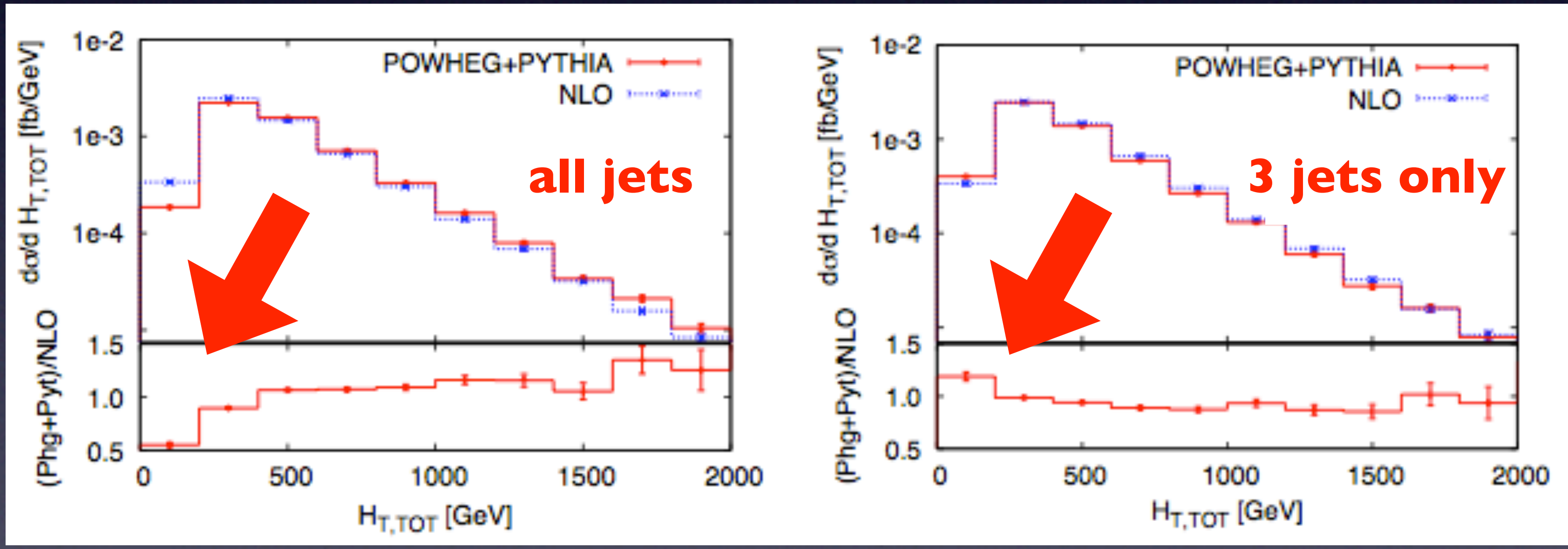
POWHEG BOX

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

POWHEG BOX: framework to automatically shower NLO calculations

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

Melia, Nason, Rontsch, GZ 1102.4846



☛ the level of agreement depends on the observable

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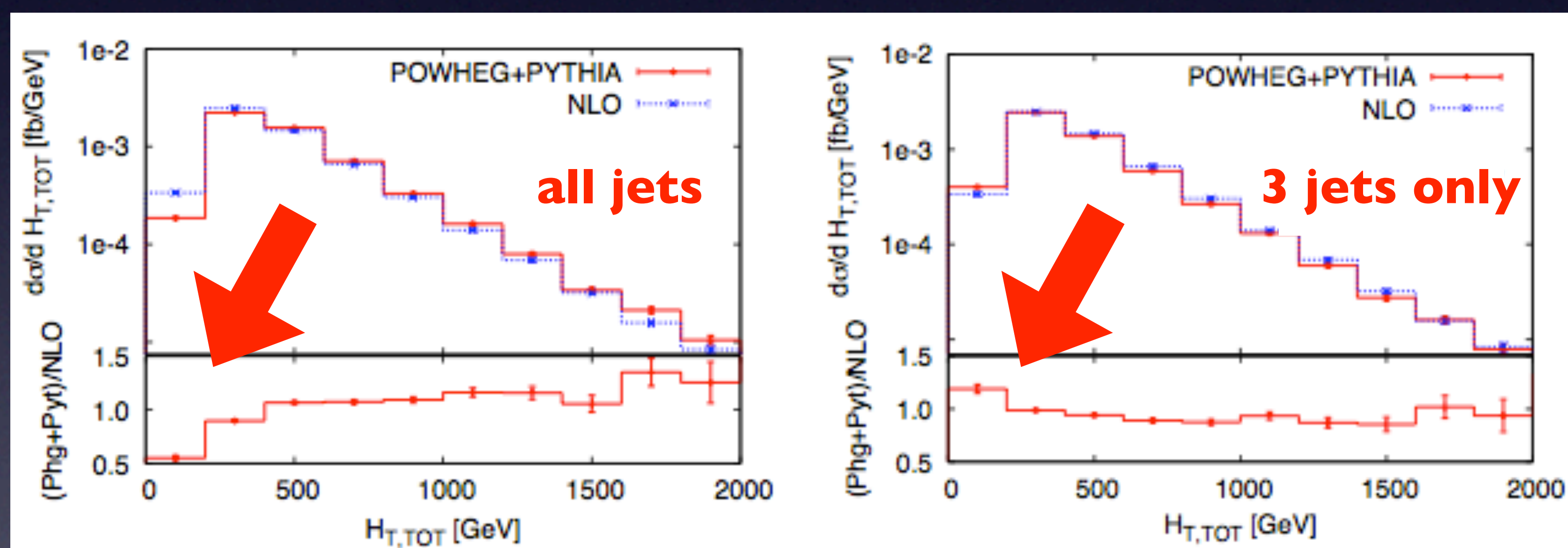


☛ the level of agreement depends on the observable

Also very recent:

aMC@NLO = automated complete event generation at NLO

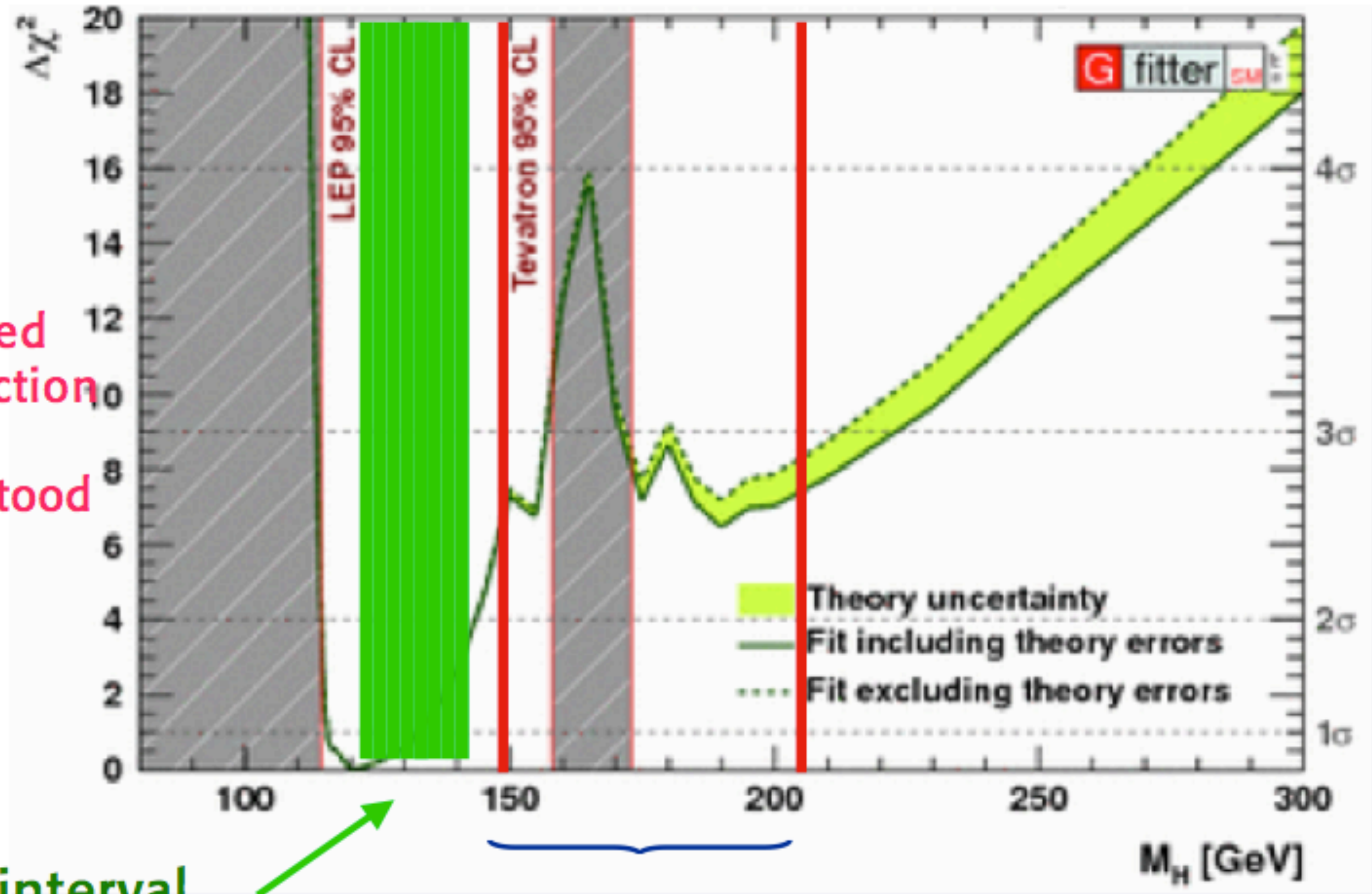
Hirschi et al. 1104.5613

Higgs searches

➟ see talks of E. James and W. Murray

The SM Higgs is close to be observed or excluded

This fig. is a non authorized reproduction of what I understood



interval with excess ~2.5 σ

Excl. by ATLAS/CMS

also $300 < m_H < 450$ GeV is excluded

slide taken from G. Altarelli

$gg \to H$

The urge to understand EW symmetry breaking led to most advanced theoretical predictions, for instance, we know the main $gg \to H$ production mechanism in the SM including

- NLO with exact top and bottom loop — Djouadi, Graudenz, Spira, Zerwas '93,'95
- NNLO in large m_t limit — Ravindran, Smith, van Neerven '03; Kilgore and Harlander '02; Anastasiou, Melnikov '02
- electroweak corrections — Actis, Passarino, Sturm, Uccirati '08
- mixed QCD - EW corrections — Anastasiou, Boughezal, Petriello '09
- resummation and/or N^3LO soft — Catani, De Florian, Grazzini, Nason '03; Moch and Vogt '05; Laenen, Magnea '06; Ahrens, Becher, Neubert, Yang '08
- fully exclusive decays to $\gamma\gamma$, $WW \to l^+l^- \nu\nu$ and $ZZ \to 4l$ — Catani and Grazzini '08; Anastasiou, Melnikov Petriello '05; Anastasiou, Dissertori, Stoeckli '07
- also exclusive NNLO $VH(\to bb)$ — Ferrera, Grazzini, Tramontano '11

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So, how well do we know this process?
What is the theory error on it ?

- electroweak corrections — Actis, Passarino, Sturm, Uccirati '08
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You'll find quoted errors ranging from10% to 40%

- also exclusive NNLO VH(→bb) — Ferrera, Grazzini, Tramontano '11

Assigning a theoretical error very important to claim exclusion/excess, and for measurements of couplings. Yet, even for the main Higgs production channel there are still controversies. I will illustrate here two of them.

π^2 resummation in Higgs

- soft logarithms can be resummed using an effective theory
- the calculation requires a matching scale, where full and effective theory amplitude agree
- choosing a time-like matching scale effectively resums π^2 terms

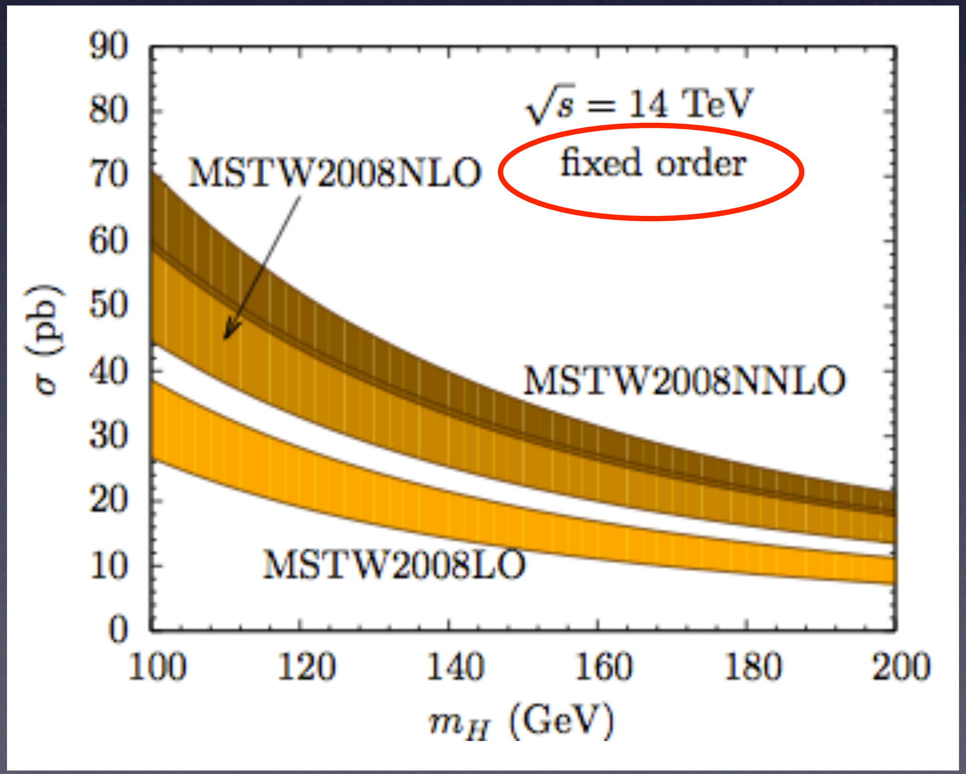
Higgs Handbook, 1101.0593

Criticism:

- π^2 are just numbers, there is no limit in which they dominate
- only π^2 that come from gluon form factor are resummed (not all)

However, practically "π^2 resummation" improves convergence of perturbative expansion significantly

Ahrens et al. '08



See also: predictions at 7 TeV including EW corrections in Ahrens et al. '11

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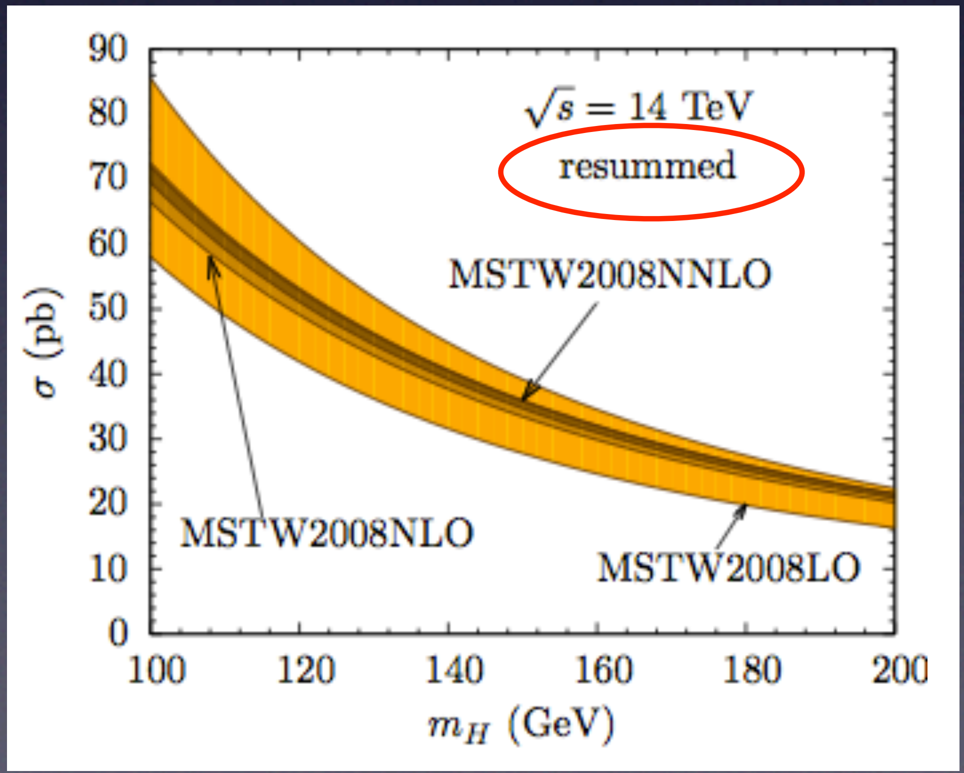

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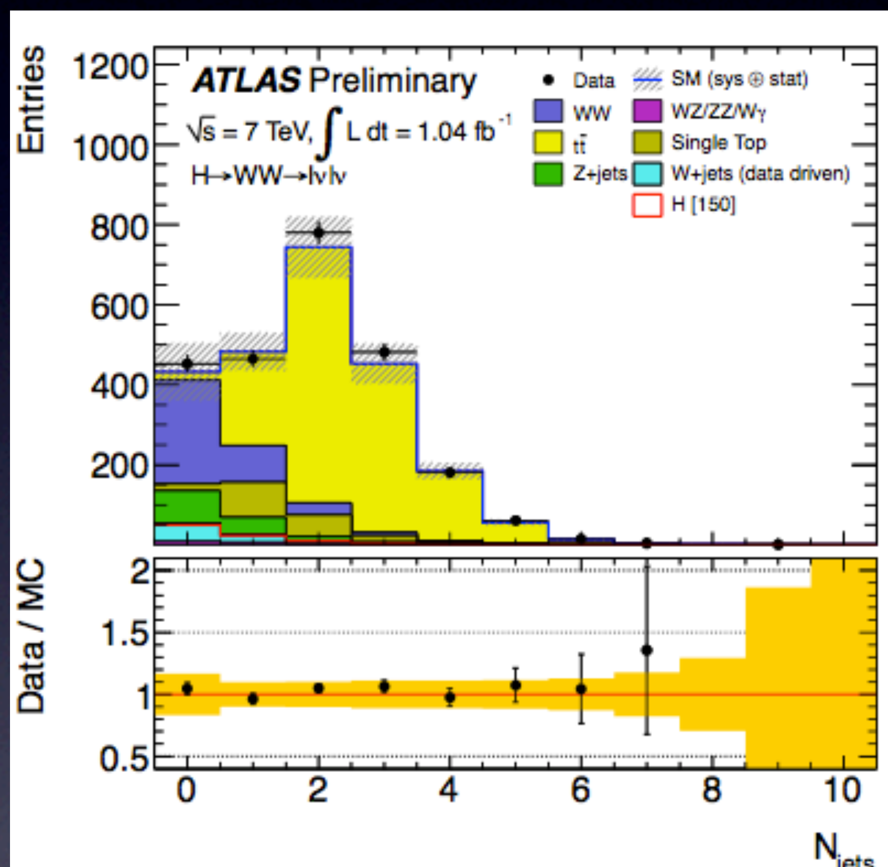
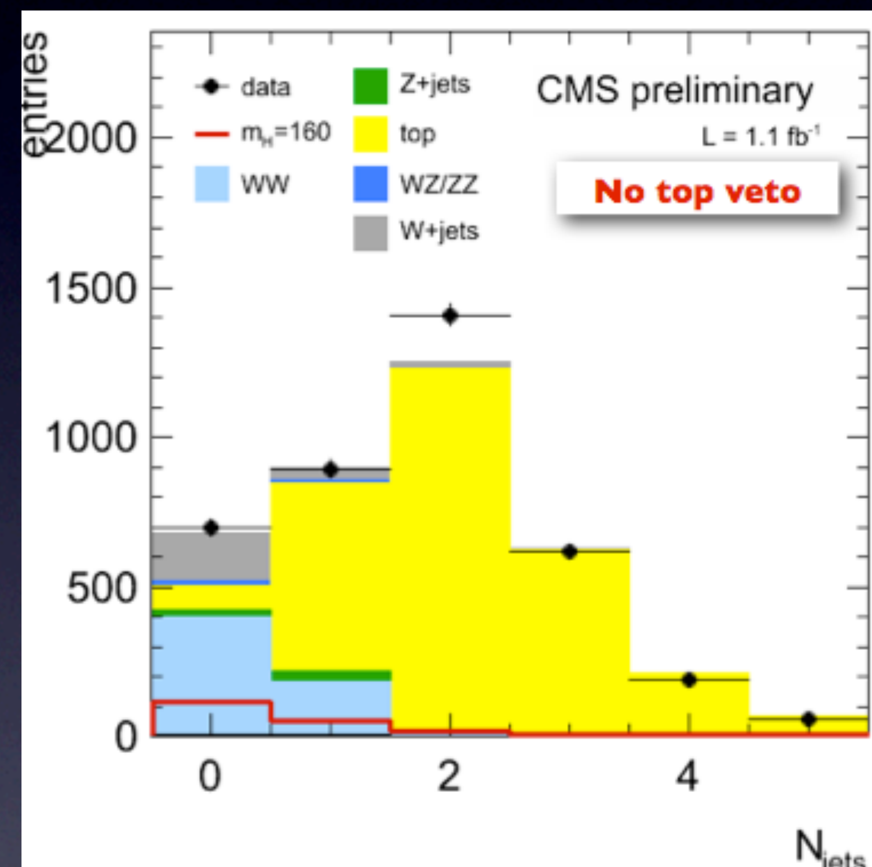
Jet veto for Higgs

Need jet veto to kill large top background, ideally $p_T^{veto} \approx 25$ GeV





Higgs production studied in 0-,1-,2-jet bin separately to maximize sensitivity

Tevatron →
$$\frac{\Delta\sigma_{tot}}{\sigma_{tot}} = 66.5\%^{+5\%}_{-9\%} + 28.6\%^{+24\%}_{-22\%} + 4.9\%^{+78\%}_{-41\%} = [-14.3\%; +14.0\%]$$

NB: $\mu_R = \mu_F$ — 0-jet — 1-jet — ≥2-jets

Anastasiou et al. 0905.3529

Jet veto for Higgs

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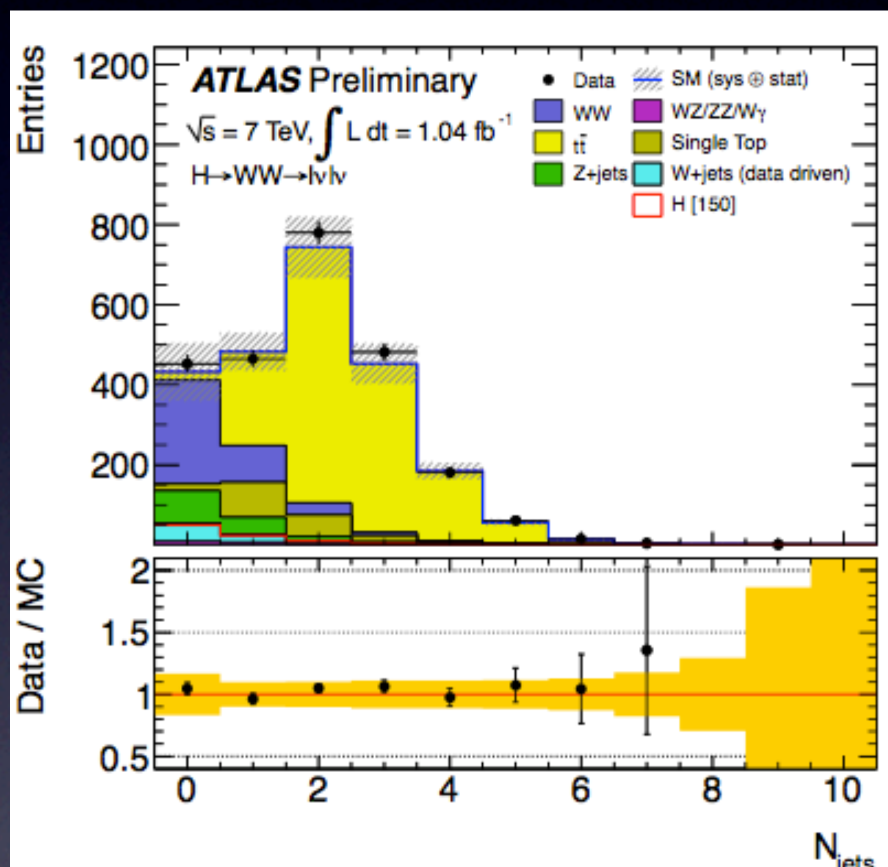
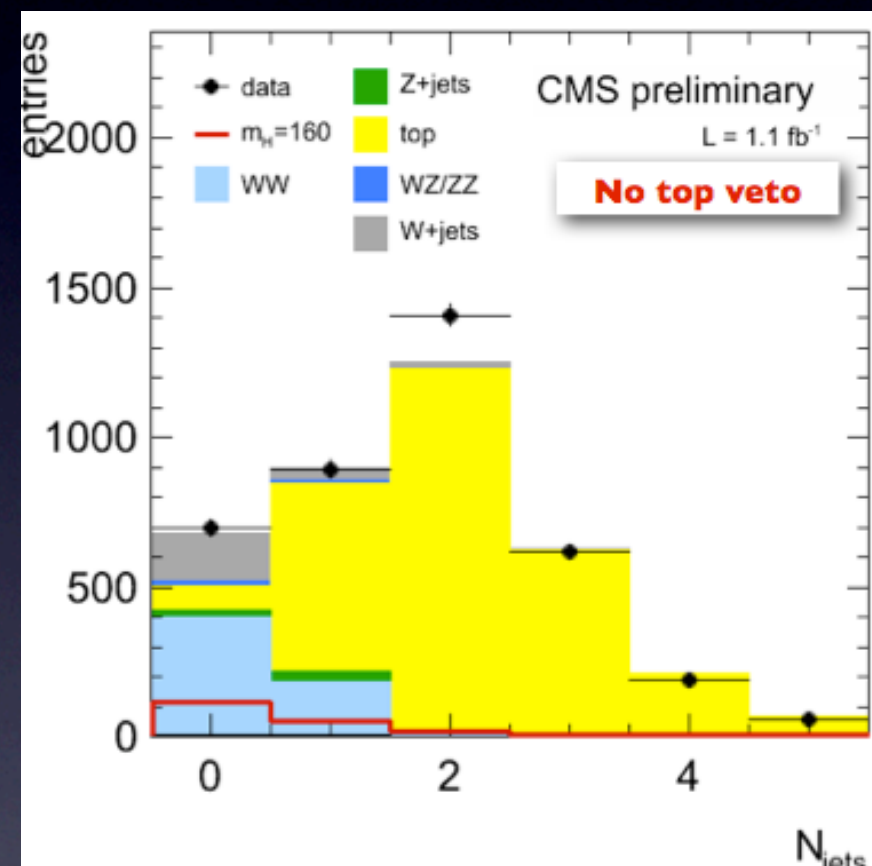




Higgs production studied in 0-,1-,2-jet bin separately to maximize sensitivity

Tevatron →

$$\frac{\Delta\sigma_{\rm tot}}{\sigma_{\rm tot}} = 60\%^{+5\%}_{-9\%} + 29\%^{+24\%}_{-23\%} + 11\%^{+35\%}_{-31\%} = [-15.5\%; +13.8\%]$$

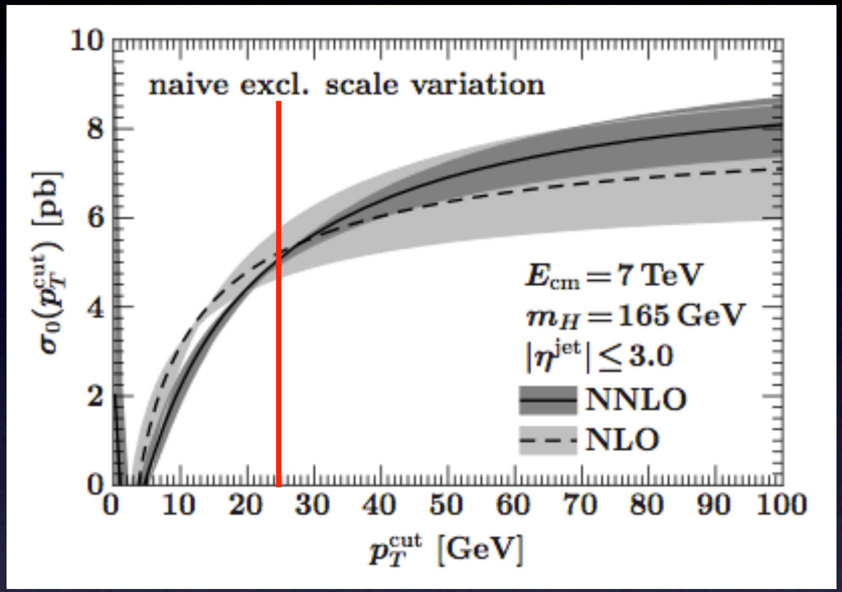
0-jet 1-jet ≥2-jets

NB: $\mu_R = \mu_F$

Anastasiou et al. 0905.3529
Update by Campbell, Ellis, Williams 1001.4495

Jet veto for Higgs

Stewart and Tackman '11



- with p_T^{veto} much smaller error
- large positive correction (K-fact.) and large negative logarithms

$$-\frac{2C_A\alpha_s}{\pi}\ln^2\frac{M_H}{p_T^{veto}}$$

Jet veto for Higgs

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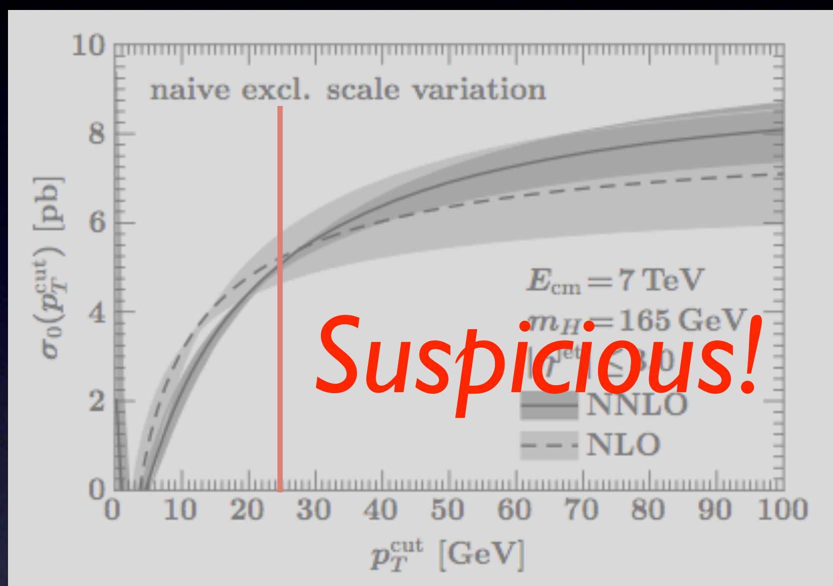

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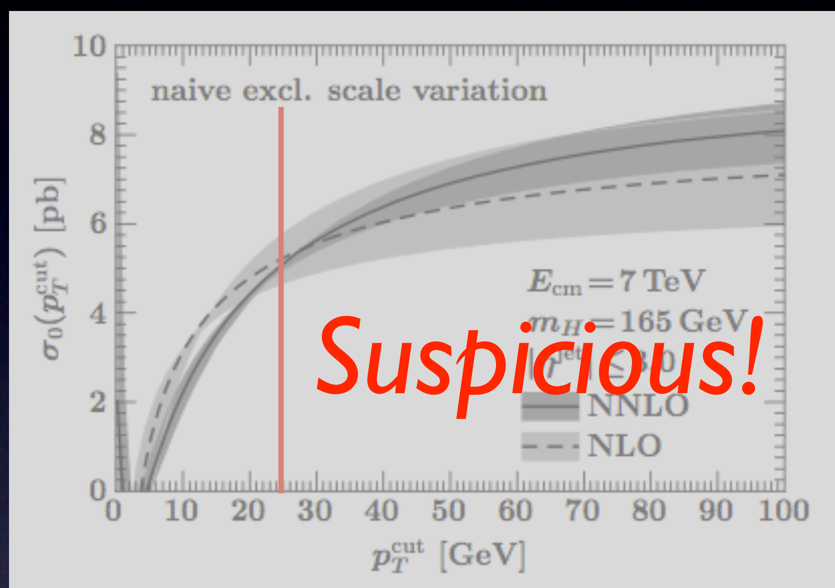

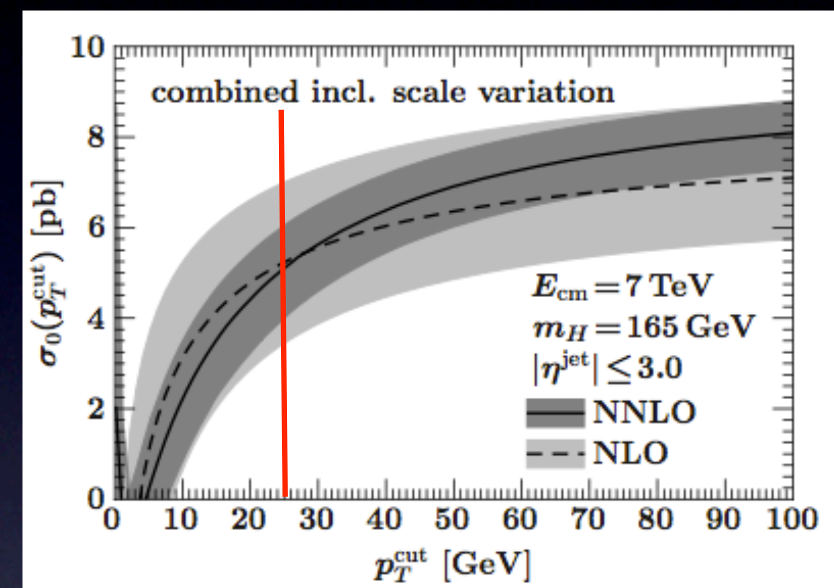

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- with correlations between jet bins

large K *large logarithms*

$$\sigma_{0\,\mathrm{jets}} = \sigma_{\mathrm{tot}} - \sigma_{\geq 1\,\mathrm{jet}}$$

$$\Delta^2\sigma_{0\,\mathrm{jets}} = \Delta^2\sigma_{\mathrm{tot}} + \Delta^2\sigma_{\geq 1\,\mathrm{jet}}$$

Jet veto for Higgs

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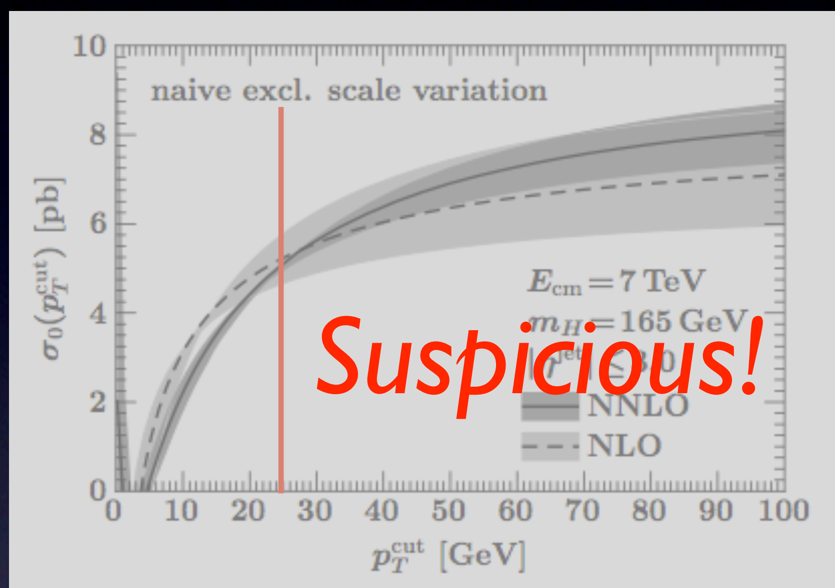

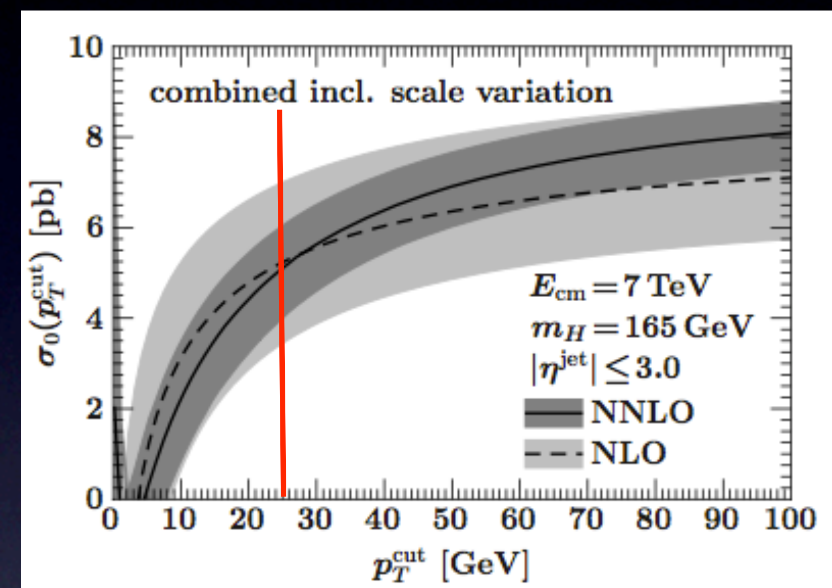

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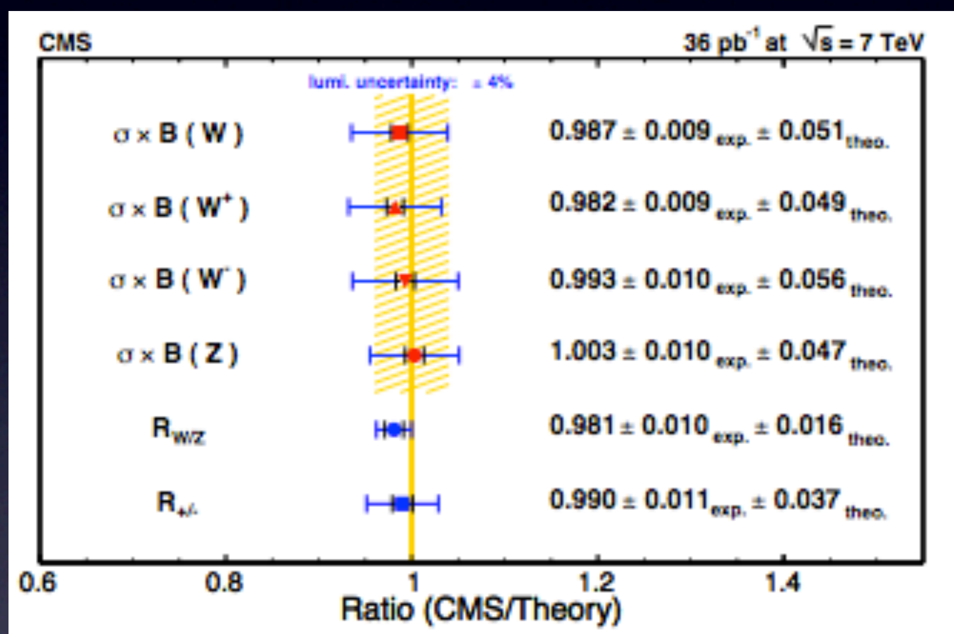
Resummation only for related quantities exist (p_T^{Higgs}, beam-thrust)

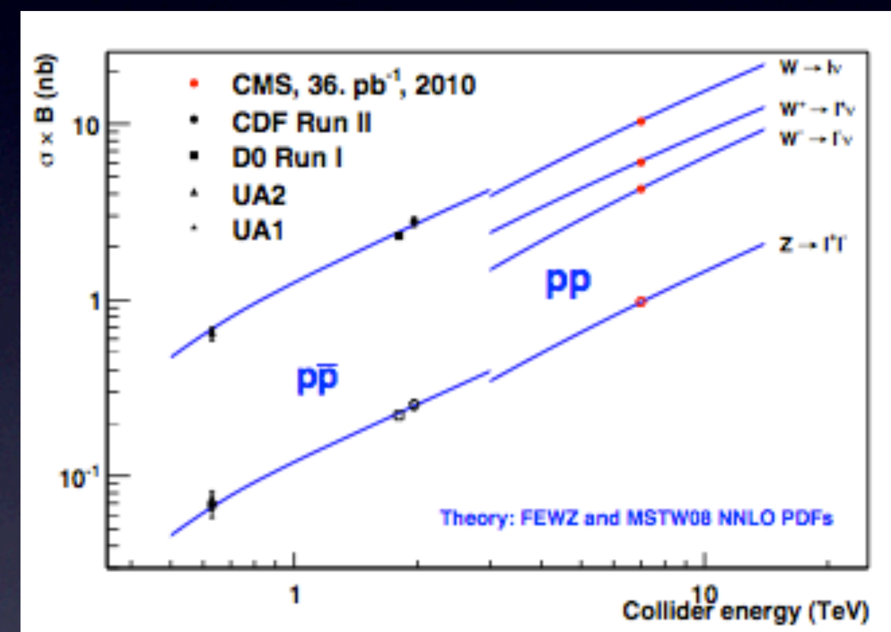
Bozzi, Catani, DeFlorian, Grazzini '03; Berger, Marcantonini, Stewart, Tackmann, Waalewijn '11

NNLO: DY

➟ see talk of J. Alcaraz

Impressive agreement between experiment and NNLO theory





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

CMS PAS EWK-10-005, similar results from ATLAS not shown here

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 . . .

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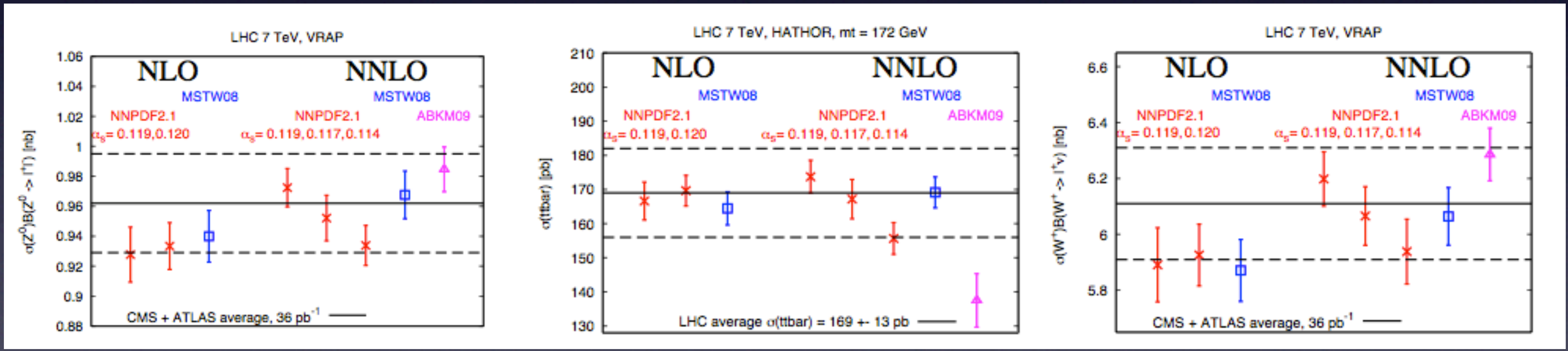
Uncertainty from pdfs and α_s on benchmark processes

NNpdfs 1107.2652



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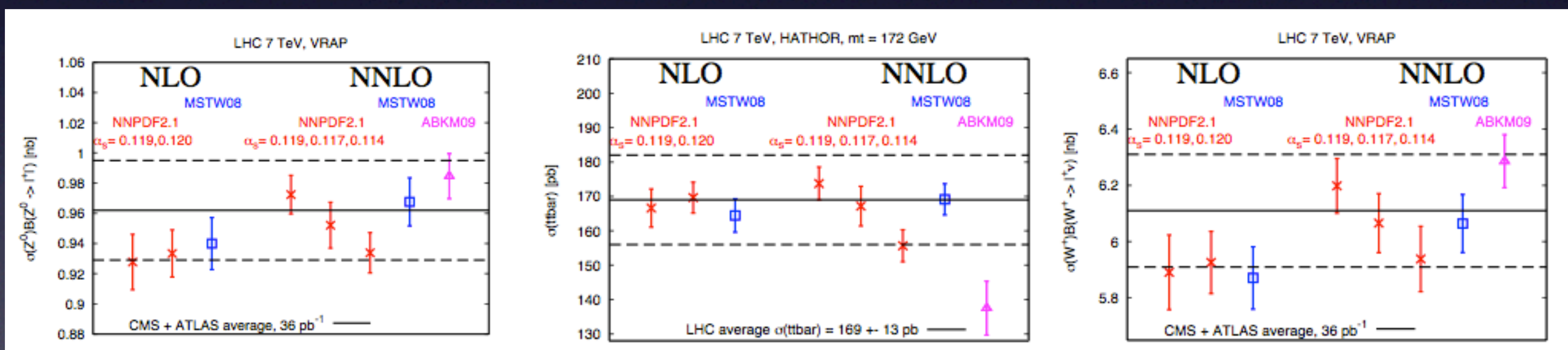

<u>Differences due to:</u>

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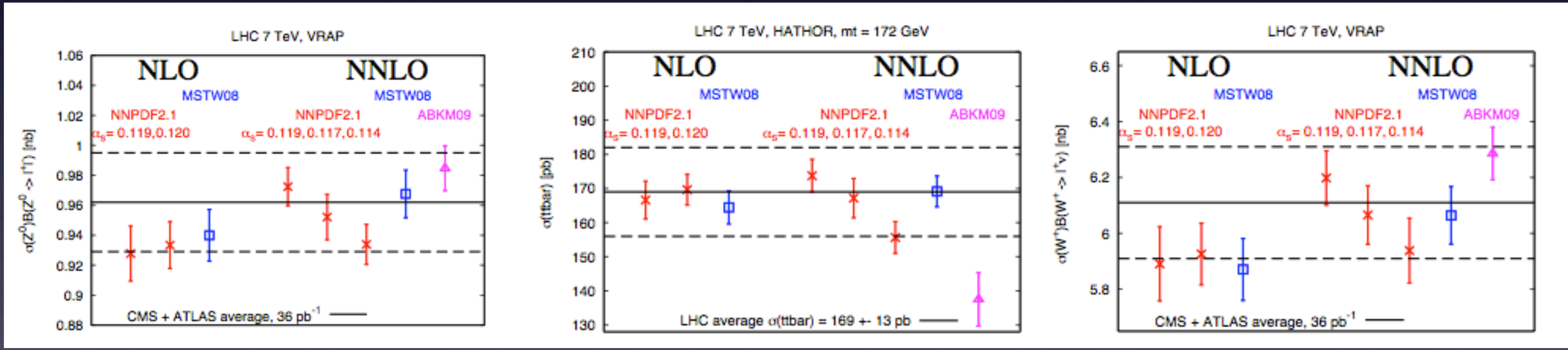

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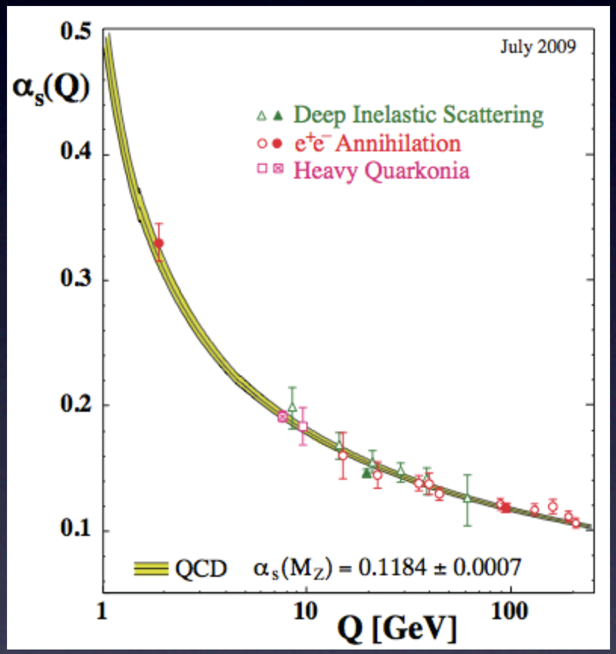
α_s in year 2011

2009 world summary

$\alpha_s = 0.1184 \pm 0.0007$



α_s in year 2011

dedicated workshop in Munich in February 2011
Courtesy of S. Bethke

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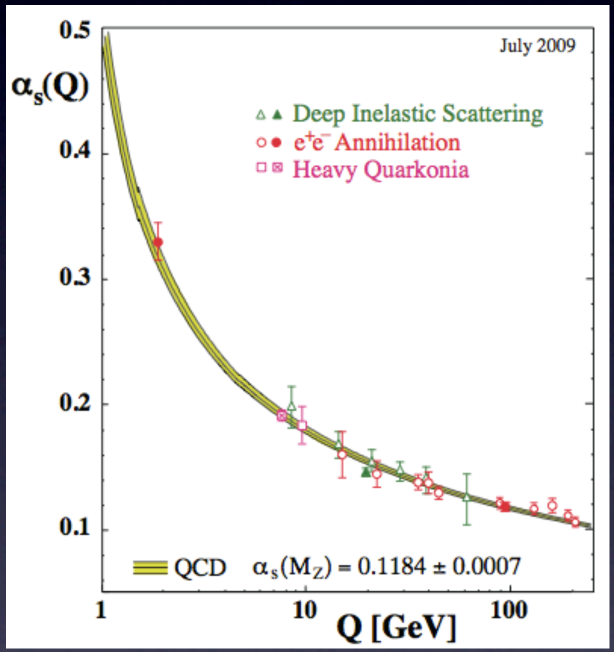

Very preliminary July 2011 # : $\alpha_s = 0.1183 \pm 0.0010$

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

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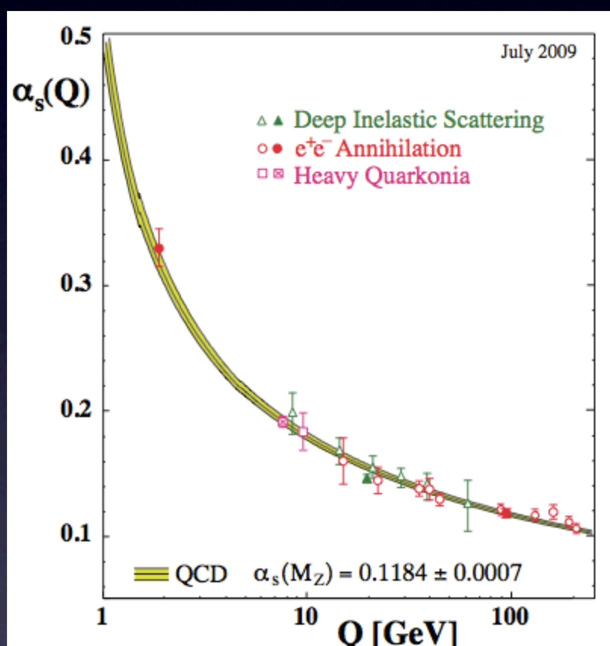

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Open issue: treatment of very accurate outliers e.g.

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

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

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

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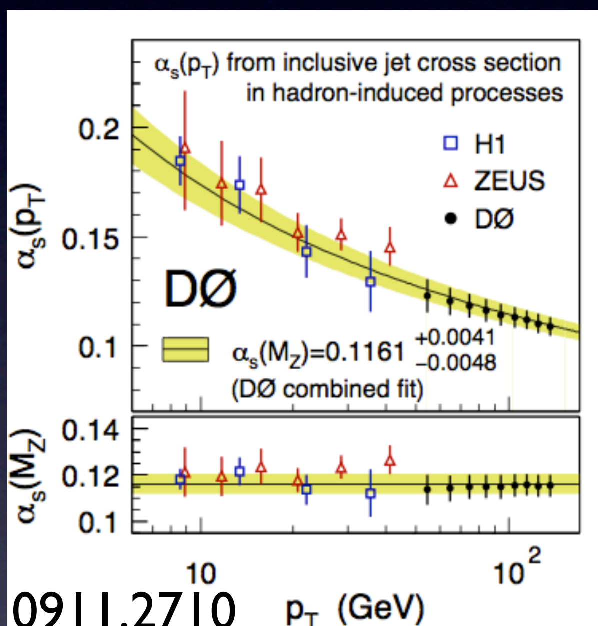

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new

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Lattice QCD	7.5	0.1183 ± 0.0008	0.1182 ± 0.0017	0.1
Υ decays	9.46	$0.119^{+0.006}_{-0.005}$	0.1183 ± 0.0010	0.1
e^+e^- [jets & shps]	14 - 44	0.1172 ± 0.0051	0.1183 ± 0.0010	0.2
→ $p\bar{p}$ incl. jets	50-145	0.1161 ± 0.0045	0.1183 ± 0.0010	0.4
e^+e^- [ew prec. data]	91.2	0.1193 ± 0.0028	0.1182 ± 0.0010	0.4
→ e^+e^- [jets & shps]	91 - 208	0.1208 ± 0.0038	0.1182 ± 0.0011	0.7
→ e^+e^- [5-jet]	91 - 208	$0.1155^{+0.0041}_{-0.0034}$	0.1183 ± 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^{3}LO]
Abbate et al. 1106.3080

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

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

Top

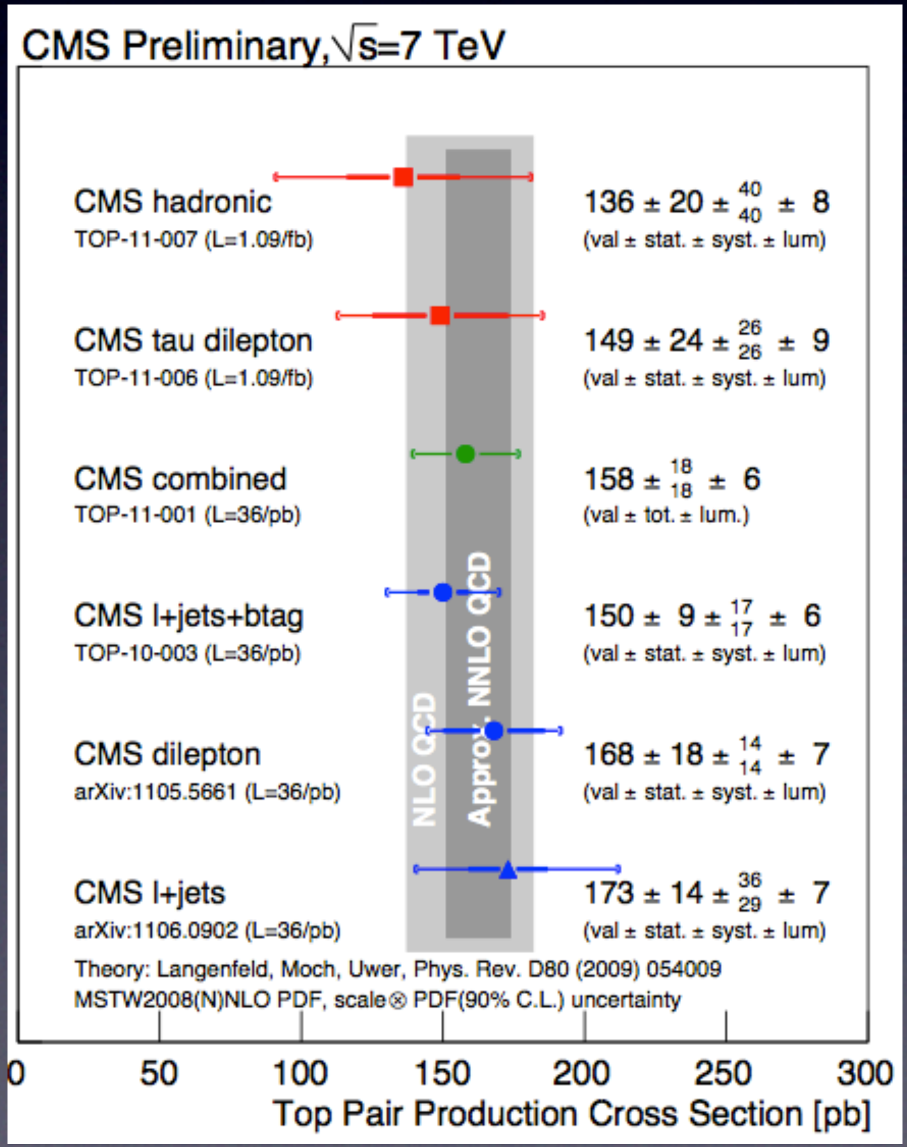
Large Yukawa coupling and prominent decay product in many new-physics models. The place where new physics will show up?

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

The frontier of NNLO

[. . .]

➟ see talk of F. Deliot



<u>Motivation for NNLO</u>

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

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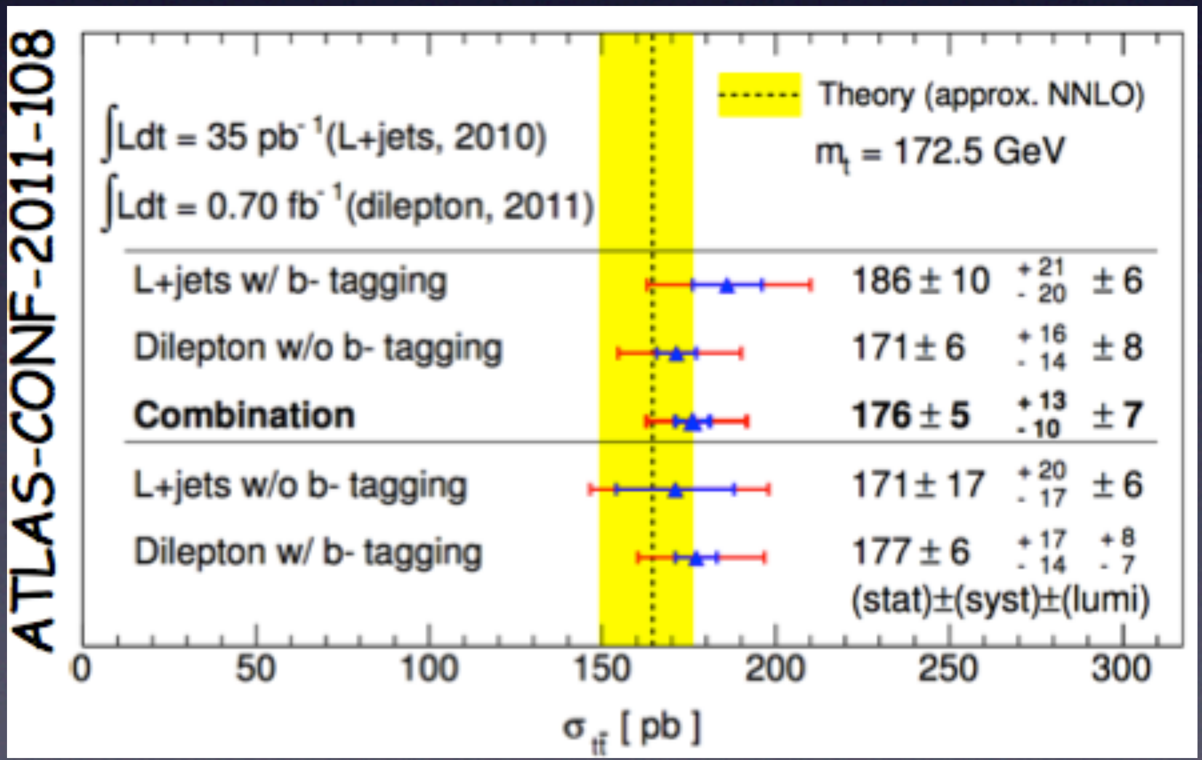
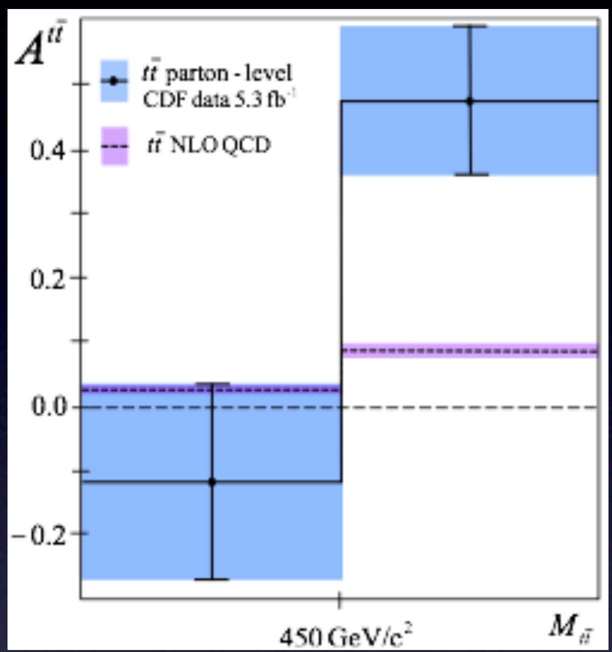


<u>Motivation for NNLO</u>

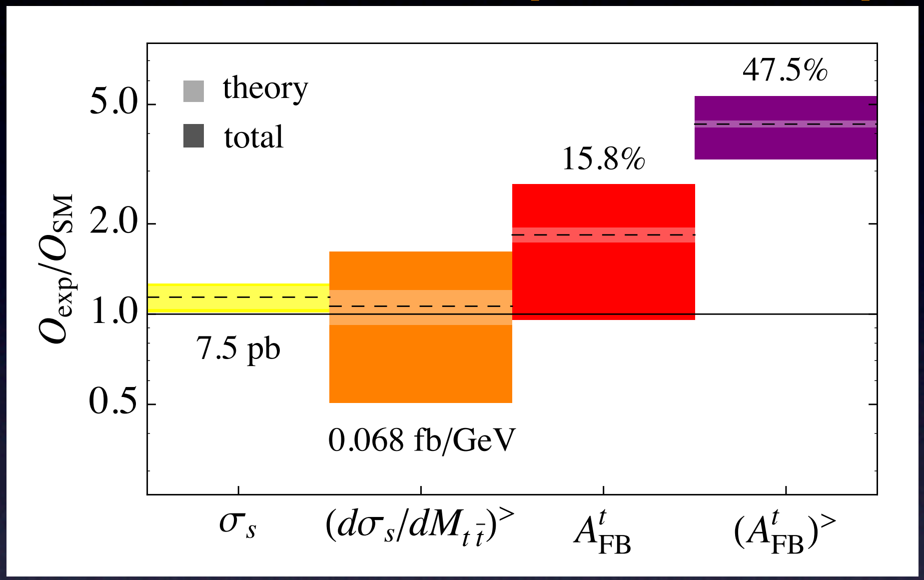
- constrain gluon pdf
- top mass from cross-section
- top FB asymmetry

Top charge asymmetry



CDF 1101.0034

Tension between sym. and asym.



➟ see talk by S. Westhoff

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 ...

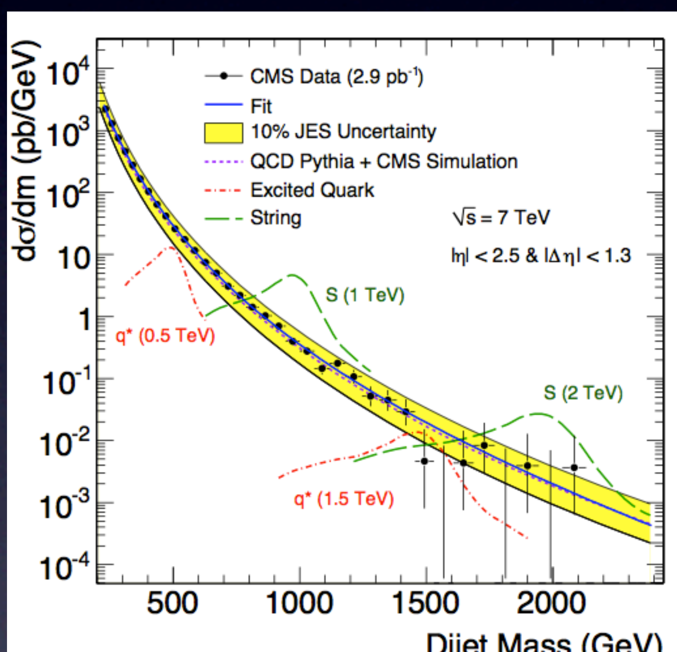
Various new models try to explain data, but difficult to preserve good agreement with symmetric cross-section, like-sign top decays, ...

Jet algorithms

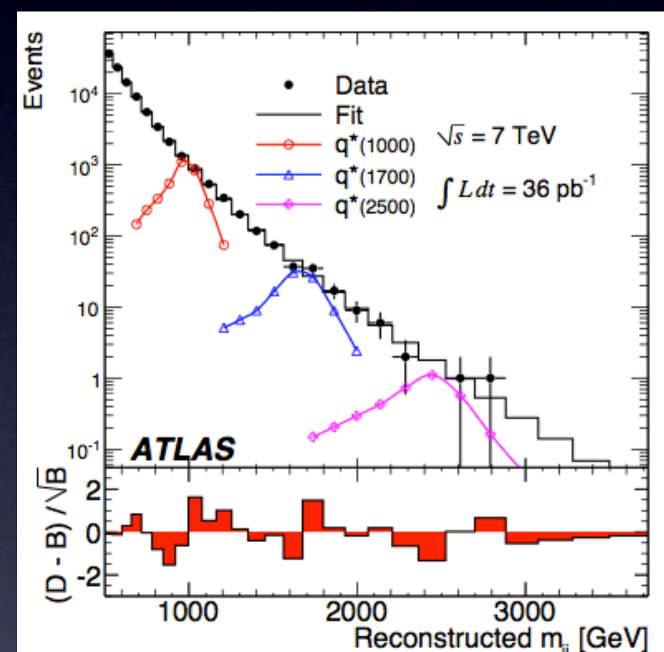
ATLAS and CMS adopted as default jet-algorithm: anti-k_t

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

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

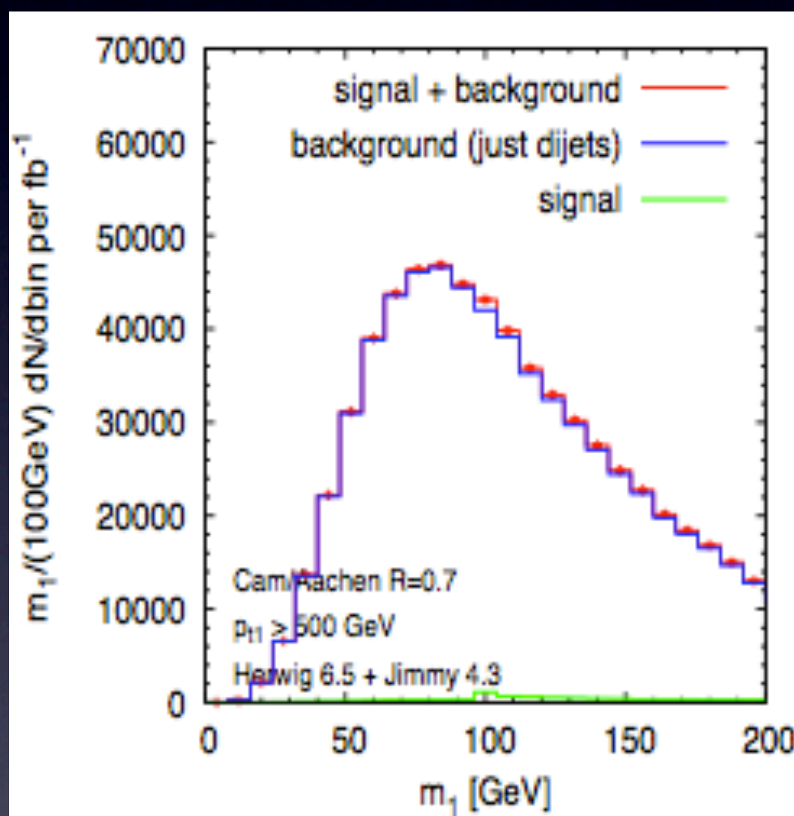
\+ big gain in sensitivity over traditional methods

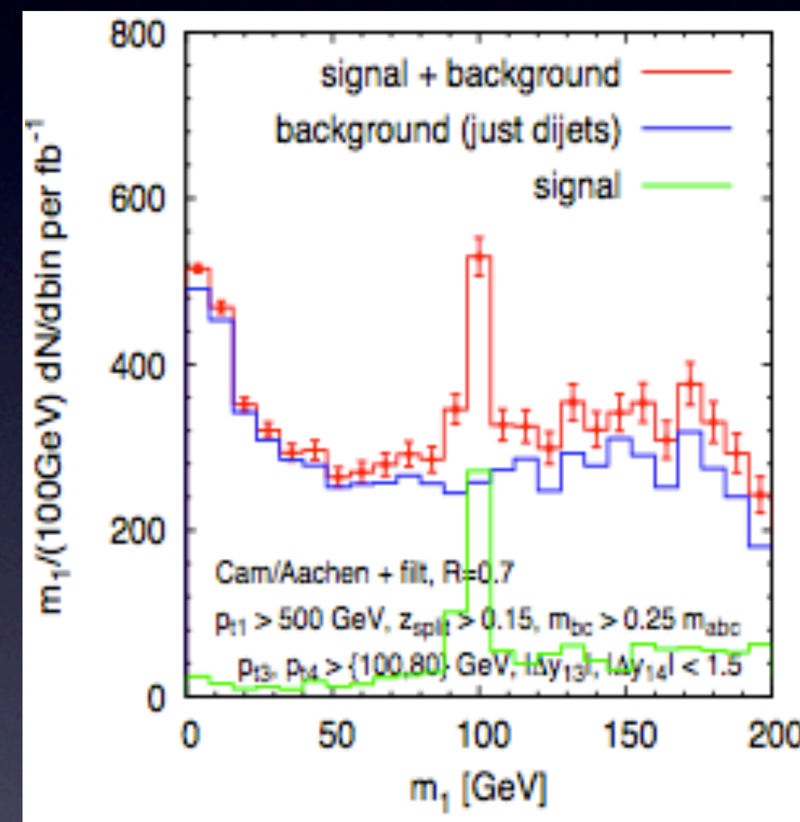
− might lose many events with boosted regime and kinematical cuts

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

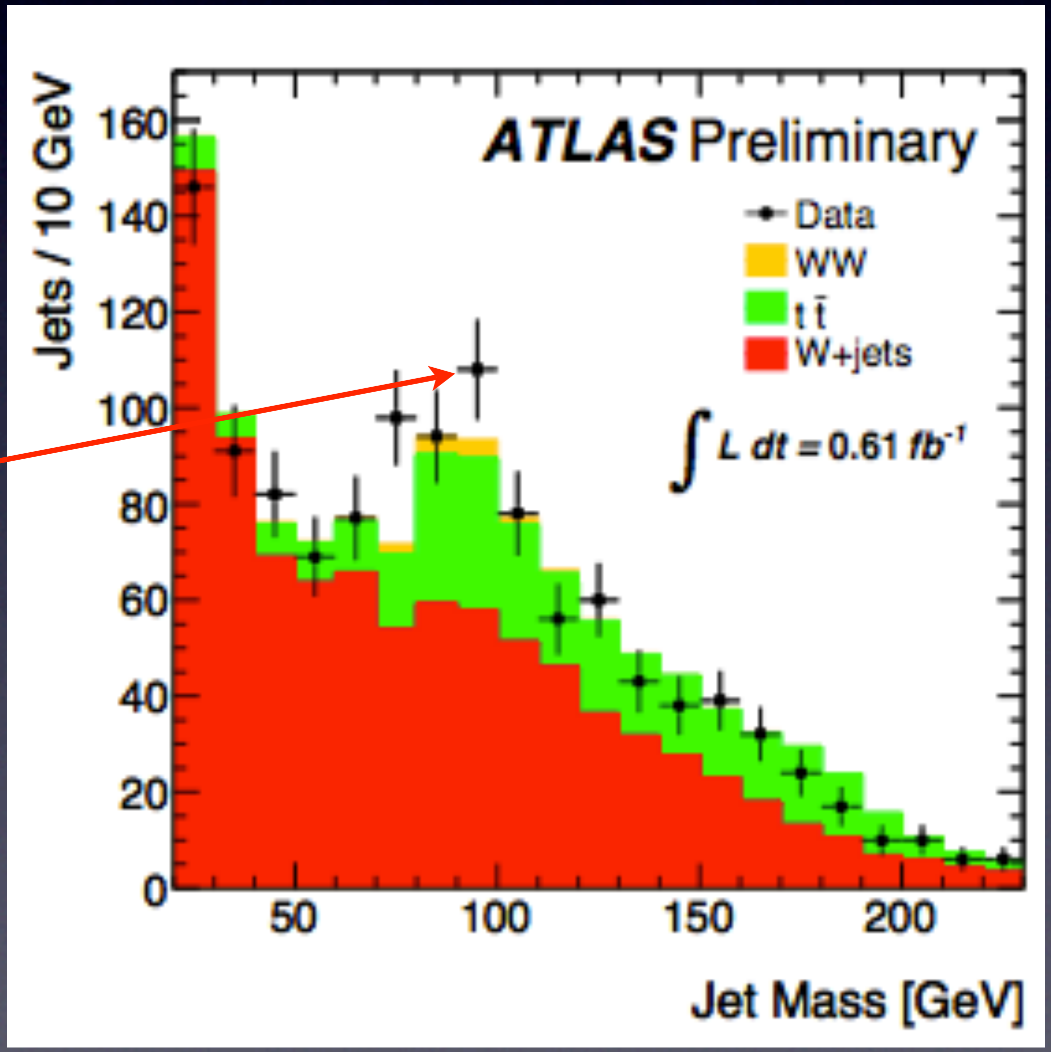
Sophisticated jet studies a young field. No precise rules for systematically making discoveries easier. Potential demonstrated, more "work in progress"

Jets in SUSY

New methods already in use at the LHC

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

Z peak evident. Very promising
Expect many new results with boosted techniques at higher statistics soon



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, ...]
- ...

➟ see talk of L. Dixon

"True genius resides in the capacity for evaluation of uncertain, hazardous, and conflicting information."

W. Churchill

Spectacular results presented here but there is still lots more to come out of the LHC. We are well prepared to get the most out of it.

Thank you for your attention

Credits

Many thanks to

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for very useful discussions

Apologies

For a personal bias and an incomplete coverage of some topics, in particular highly technical advances that are essential for phenomenological studies