Summary & Outlook: Theory

QCD in the age of the LHC

Fred Olness

SMU

DESY
6 September 2013

PHYSICS AT THE TERA SCALE
Helmholtz Alliance

DESY

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The public took notice

Huge success of the HEP Community

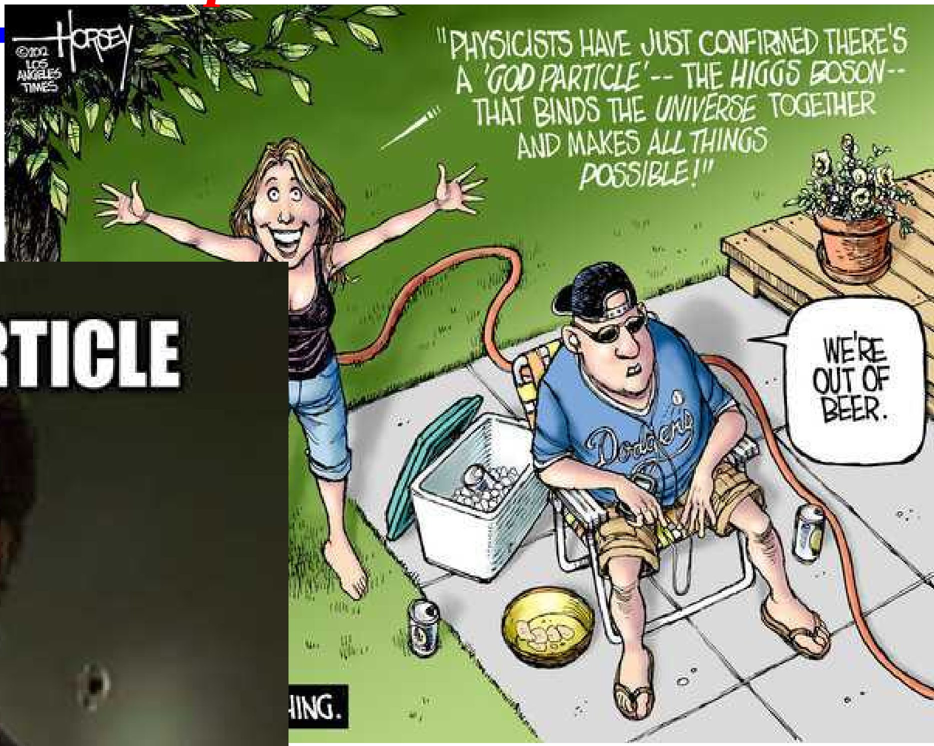
4.7.2012 greeting Melbourne from CERN

"The Higgs: So simple and yet so unnatural" G.Altarelli,arXiv:1308.0545

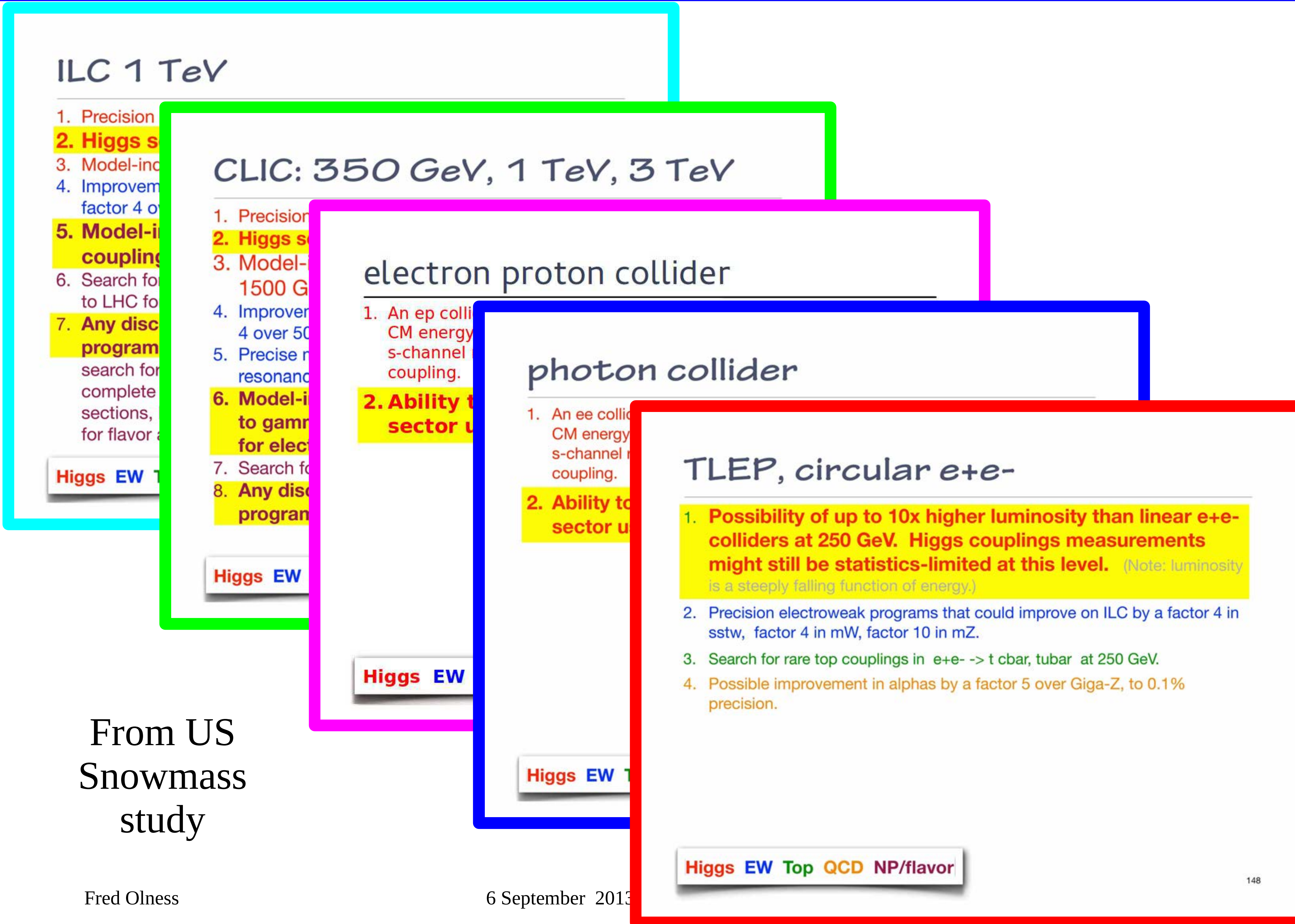
Klein


TEN MYTHS ABOUT RUSSIA
JAPAN: HOT GREEN CARS
Newsweek
The Biggest Experiment Ever
(And It's European)
The Economist
A giant leap for science
Science
BREAKTHROUGH of the YEAR
The HIGGS BOSON
DER SPIEGEL
DAS TOR ZU EINER ANDEREN WELT
Physiker entschlüsseln das Geheimnis der Anti-Materie
Volume 716, Issue 1, 17 September 2012
ISSN 0370-2693
ELSEVIER
PHYSICS LETTERS B
SciVerse ScienceDirect
CMS
ATLAS
TIME
FABIOLA GIANOTTI

… like it or not, Higgs Boson is in the public lexicon



Science Communication is Essential



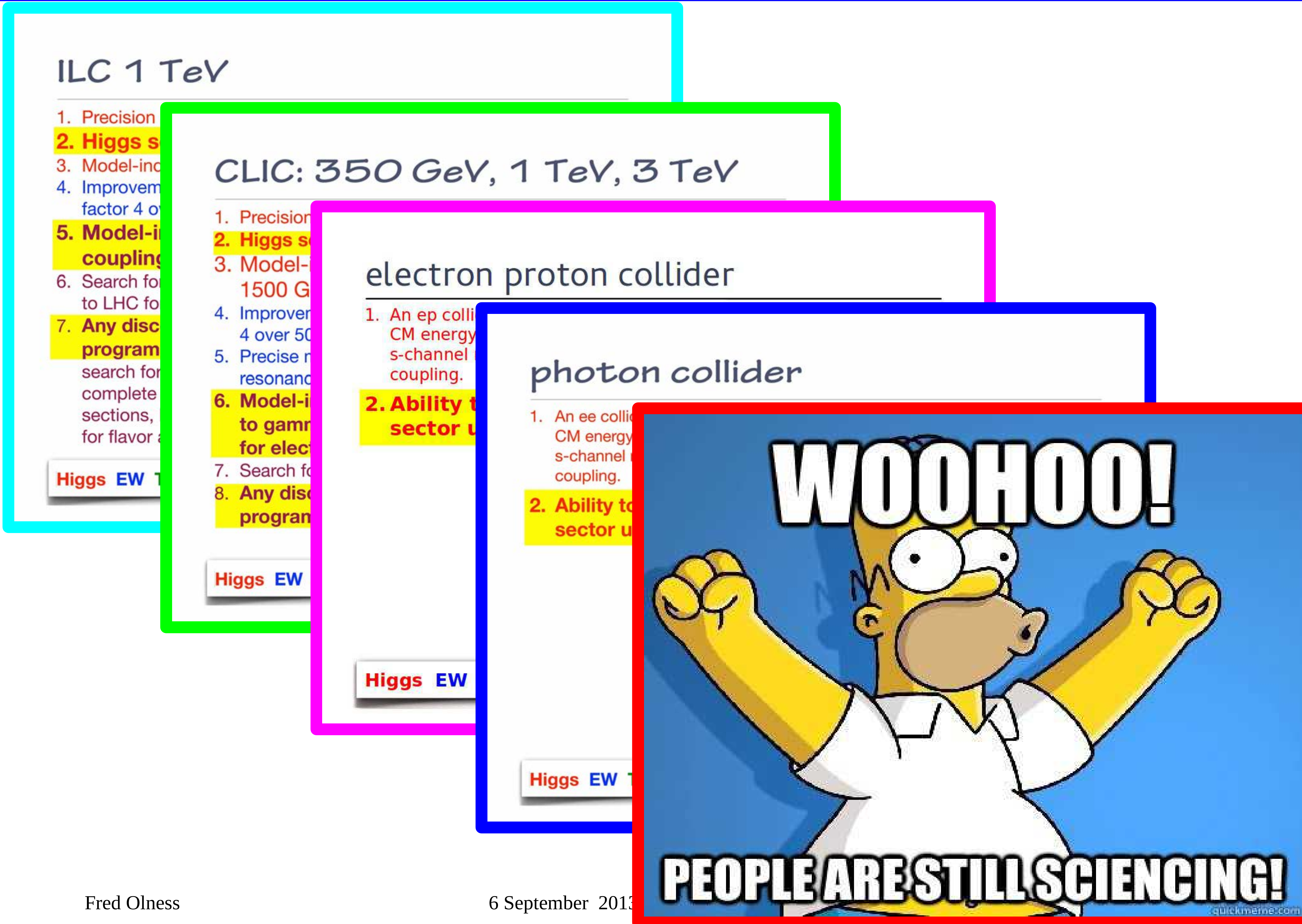
From US Snowmass study

The view from Fermilab

Highway 88:
Illinois
Technology & Research Corridor

- 50+ Major Companies
- 15+ Universities & Colleges

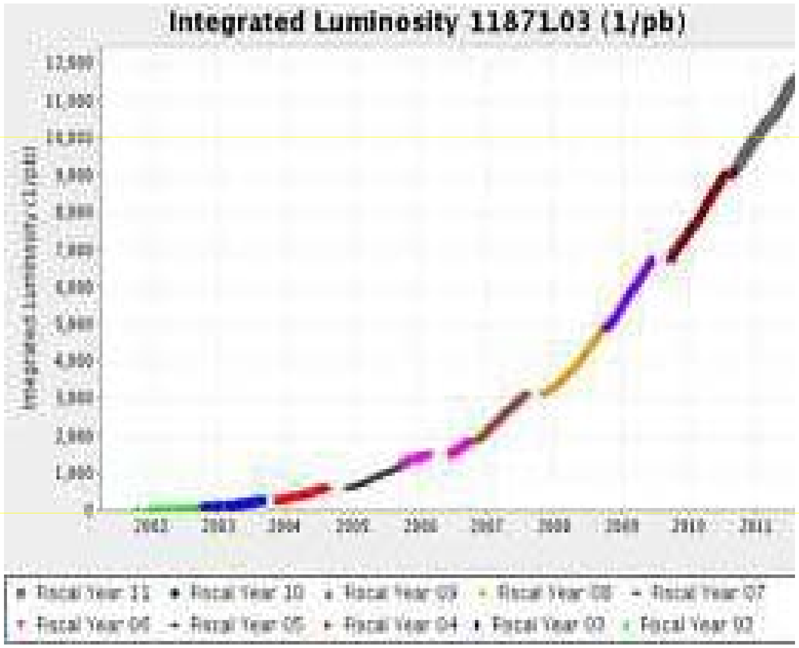
Science Communication is Essential

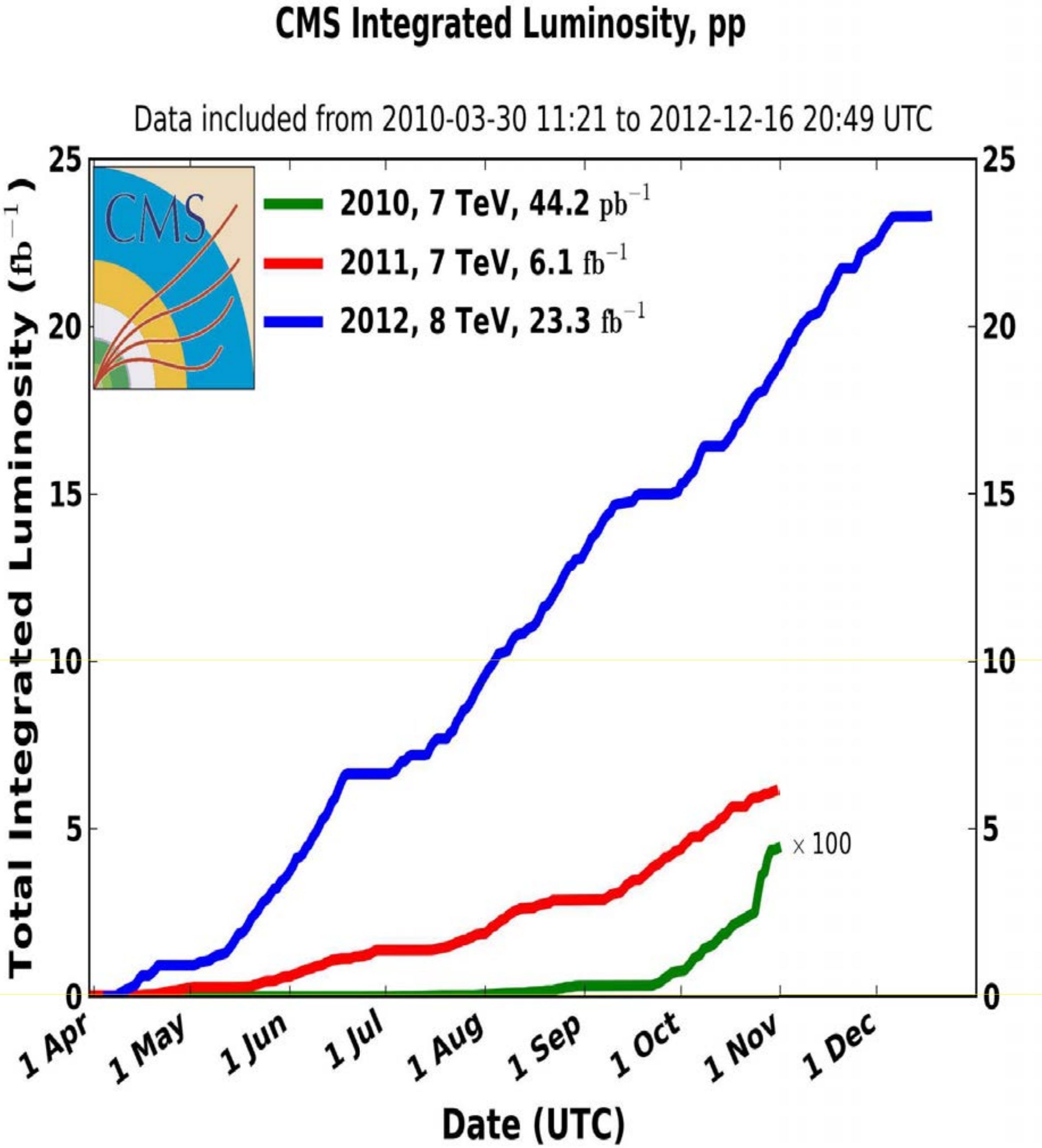


The age of the LHC

… things are different

Exhibit #1


Integrated Luminosity 11871.03 (1/pb)


CMS Integrated Luminosity, pp
Data included from 2010-03-30 11:21 to 2012-12-16 20:49 UTC
2010, 7 TeV, 44.2 pb^{-1}
2011, 7 TeV, 6.1 fb^{-1}
2012, 8 TeV, 23.3 fb^{-1}
CMS
× 100
Total Integrated Luminosity (fb^{-1})
0
5
10
15
20
25
1 Apr
1 May
1 Jun
1 Jul
1 Aug
1 Sep
1 Oct
1 Nov
1 Dec
Date (UTC)

DATA MAKES YOU SMARTER

It doesn't matter how beautiful your theory is, it doesn't matter how smart you are. If it doesn't agree with experiment, it's wrong.

Richard P. Feynman

THEORY:

- NLO Calculation typically the state of the art
  - Number of NLO calculations limited; each by hand
  - First NLO inclusive Jet Calculation
- 10+ years away from NLO + Monte Carlo merging
- Resummation: CSS (1985) but no ResBos or FEWZ
- Top quark: undiscovered
- W/Z: Recently discovered
- s(x) PDF: very uncertain *(although we didn't know it yet)*

EXPERIMENT:

Ready for Tevatron Run

Ready for HERA run

Rise of F2 at low x

Rapidity Gaps

Log scaling

Clever people figured out creative ways to push the frontier even further

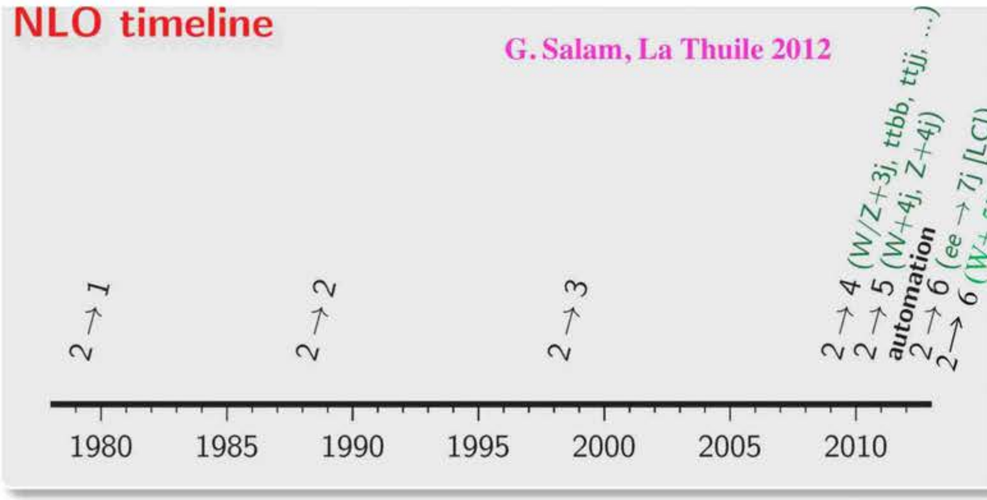
COMPUTING: Main-Frames: *Dec VAX, Cray, CDC*

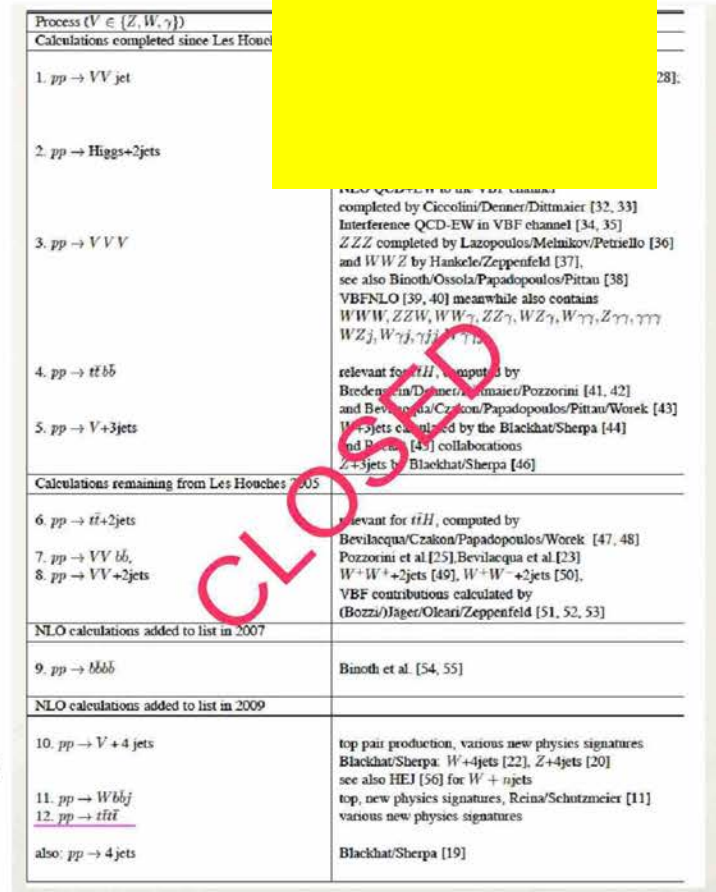
HIGHER ORDER CALCULATIONS

WOW!!!

NLO multi-parton production

- Enormous progress in getting NLO predictions for 2→(4,5,6!) processes over the last years





Process ($V \in \{Z, W, \gamma\}$)	
Calculations completed since Les Houc[illegible]	
1. $pp \to VV$ jet	[illegible] 28];
2. $pp \to$ Higgs+2jets	[illegible] completed by Ciccolini/Denner/Dittmaier [32, 33] Interference QCD-EW in VBF channel [34, 35]
3. $pp \to VVV$	ZZZ completed by Lazopoulos/Melnikov/Petriello [36] and WWZ by Hankele/Zeppenfeld [37], see also Binoth/Ossola/Papadopoulos/Pittau [38] VBFNLO [39, 40] meanwhile also contains $WWW, ZZW, WW\gamma, ZZ\gamma, WZ\gamma, W\gamma\gamma, Z\gamma\gamma, \gamma\gamma\gamma$ $WZj, W\gamma j, \gamma jj$ [illegible]
4. $pp \to t\bar{t}b\bar{b}$	relevant for $t\bar{t}H$, computed by Bredenstein/Denner/Dittmaier/Pozzorini [41, 42] and Bevilacqua/Czakon/Papadopoulos/Pittau/Worek [43]
5. $pp \to V$+3jets	W+3jets calculated by the Blackhat/Sherpa [44] and R[illegible] [45] collaborations Z+3jets by Blackhat/Sherpa [46]
Calculations remaining from Les Houches 2005	
6. $pp \to t\bar{t}$+2jets	relevant for $t\bar{t}H$, computed by Bevilacqua/Czakon/Papadopoulos/Worek [47, 48]
7. $pp \to VV\, b\bar{b}$, 8. $pp \to VV$+2jets	Pozzorini et al.[25],Bevilacqua et al.[23] W^+W^++2jets [49], W^+W^-+2jets [50], VBF contributions calculated by (Bozzi/)Jäger/Oleari/Zeppenfeld [51, 52, 53]
NLO calculations added to list in 2007	
9. $pp \to b\bar{b}b\bar{b}$	Binoth et al. [54, 55]
NLO calculations added to list in 2009	
10. $pp \to V + 4$ jets	top pair production, various new physics signatures Blackhat/Sherpa: W+4jets [22], Z+4jets [20] see also HEJ [56] for $W + n$jets
11. $pp \to Wb\bar{b}j$ 12. $pp \to t\bar{t}t\bar{t}$	top, new physics signatures, Reina/Schutzmeier [11] various new physics signatures
also: $pp \to 4$ jets	Blackhat/Sherpa [19]

CLOSED

- Made possible by
  - Improved techniques for loop amplitudes
  - Crucial: a high level of automation

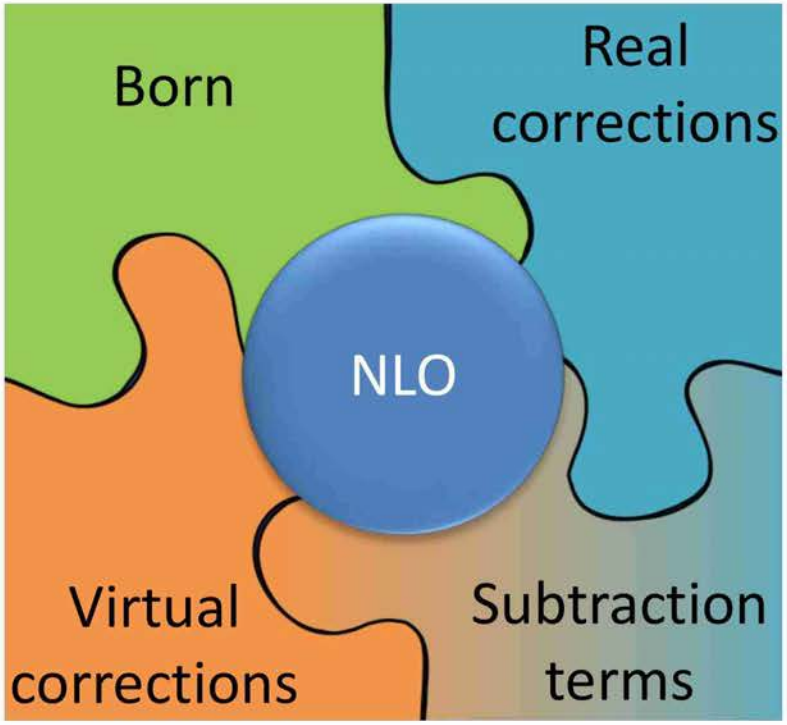
K. Melnikov, MITP, 2013

Gehrmann

Well Defined Interfaces →. Open Code/Collaboration

NLO automation

- Well-defined interfaces (Binoth Les Houches accord)
  - combine different ingredients from different codes
- One-loop amplitudes
  - BlackHat (Z. Bern, L. Dixon, F. Febres Cordero, S. Höche, H. Ita, D. Kosower, D. Maitre, K. Ozeren)
  - GoSam (G. Cullen, N. Greiner, G. Heinrich, G. Luisoni, P. Mastrolia, G. Ossola, T. Reiter, F. Tramontano)
  - OpenLoops (F. Cascioli, P. Maierhöfer, S. Pozzorini)
  - NJet (S. Badger, B. Biedermann, P. Uwer, V. Yundin)
  - MadLoop/aMC@NLO (R. Frederix et al.)
  - CutTools (G. Ossola, C. Papadopoulos, R. Pittau)
- Real radiation, subtraction terms and phase space (infrastructure)
  - Sherpa (F. Kraus et al.)
  - Madgraph/MadEvent (F. Maltoni et al.)
  - HelacNLO (G. Bevilacqua, C. Papadopoulos et al.)
  - MCFM (J. Campbell, K. Ellis, C. Williams)



Higher orders: NNLO

- NNLO corrections important to have a good control of theoretical uncertainties: (i) When NLO are large (ii) For benchmark process measured with high precision
- NNLO computations cumbersome, in hadronic collisions only few calculations exist:
  - Sector decomposition: [Binoth,Heinrich('00)]
    $pp \to H$ (gg fusion) [Anastasiou,Melnikov,Petriello('04)]→FEHIP
    Drell-Yan [Melnikov,Petriello('06)]→FEWZ
  - q_T-subtraction: [Catani,Grazzini('07)]
    $pp \to H$ (gg fusion) [Catani,Grazzini('07)]→HNNLO
    Drell-Yan [Catani,Cieri,de Florian,G.F.,Grazzini('09)]→DYNNLO
    Associated WH production [G.F.,Grazzini,Tramontano('11)]→ WNNLO
    Diphoton production [Catani,Cieri,de Florian,G.F.,Grazzini('11)]→2γNNLO
  - Antenna subtraction: [Gehrmann,Gehrmann-De Ridder,Glover('05)]
    $pp \to$2jets (gluon only) [Gehrmann,G.-De Ridder,Glover,Pires('13)]→NNLOJET
  - Non-linear mapping: [Anastasiou,Herzog,Lazopoulos('10)]
    $pp \to H$ (bb fusion) [Buehler,Herzog,Lazopoulos,Mueller('12)]
  - Sector-improved subtraction: [Czakon('10)]
    $pp \to t\bar{t}$ [Baernreuther,Czakon,Fiedler,Mitov('12),('13)]→Top++
    $pp \to H + jet$ [Boughezal,Caola,Melnikov,Petriello,Schulze('13)]

Ferrera

Higher order calculations of heavy quarks are advancing

Goals

- Complete the NNLO heavy flavor Wilson coefficients for twist-2 in the dynamical safe region $Q^2 > 20\,\mathrm{GeV}^2$ (no higher twist) for $F_2(x, Q^2)$
- Measure m_c and α_s as precisely as possible
- Provide precise CC heavy flavor corrections
- The calculat
- No private n
  since we wou
- Consequence
  - NNLO V
  - better co
  - precise m

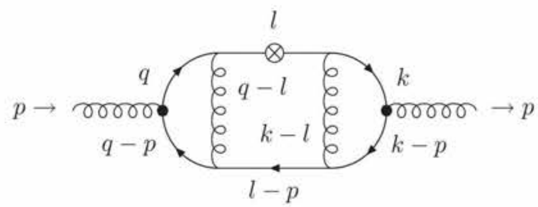
[a]For a variety of

5. Examples for Higher Topologies

Ladder Diagrams for Quarkonic OMEs

[Ablinger, Blümlein, Hasselhuhn, Klein, Schneider, Wißbrock; arXiv:1206.2252]

Let's consider the scalar integral with all powers of the propagators equal to one.



After Feynman parameterization, and performing the momentum integrals, we obtain

$$I_{1a} = \frac{i(\Delta.p)^N a_s^3 S_\epsilon^3}{(m^2)^{2-\frac{3}{2}\epsilon}} \hat{I}_{1a} \,,$$

where S_ϵ is the spherical factor $S_\epsilon = \exp\left[\frac{\epsilon}{2}(\gamma_E - \ln(4\pi))\right]$

Bluemlein

MONTE CARLOS MATCHING & MERGING

Relatively recent developments

Cornell University Library

arXiv.org > hep-ph > arXiv:hep-ph/9906316

Search or Article-id

High Energy Physics - Phenomenology

Some thoughts on how to match Leading Log Parton Showers with NLO Matrix Elements

Christer Friberg, Torbjörn Sjöstrand (Lund university, Sweden)

(Submitted on 10 Jun 1999)

We propose a scheme that could offer a convenient Monte Carlo sampling of next-to-leading-order matrix elements and, at the same time, allow the interfacing of such parton configurations with a parton-shower approach for the estimation of higher-order effects. No actual implementation exists so far, so this note should only be viewed as the outline of a possible road for the future, submitted for discussion.

Comments:	5 pages, LaTeX, no figures, to appear in the Proceedings of the DESY Workshop on "Monte Carlo Generators for HERA Physics"
Subjects:	**High Energy Physics - Phenomenology (hep-ph)**
Report number:	LU TP 99-10
Cite as:	**arXiv:hep-ph/9906316**

Two complementary approaches

MC@NLO

The subtraction terms must contain all divergencies of the real-emission matrix element. A parton shower splitting kernel does exactly that.

Generating two samples, one according to $B_n + V_n + \int S_n^{\mathrm{PS}}$, and one according to $B_{n+1} - S_n^{\mathrm{PS}}$, ... shower from which S_n is calculate...

POWHEG

Calculate $\bar{B}_n = B_n + V_n + \int B_{n+1}$ and generate n-parton states according to that.

Generate a first emission according to B_{n+1}/B_n, and then add any parton shower for subsequent emissions.

(Similar to the old first-emission matching in PYTHIA, but with a phase-space dependent K-factor).

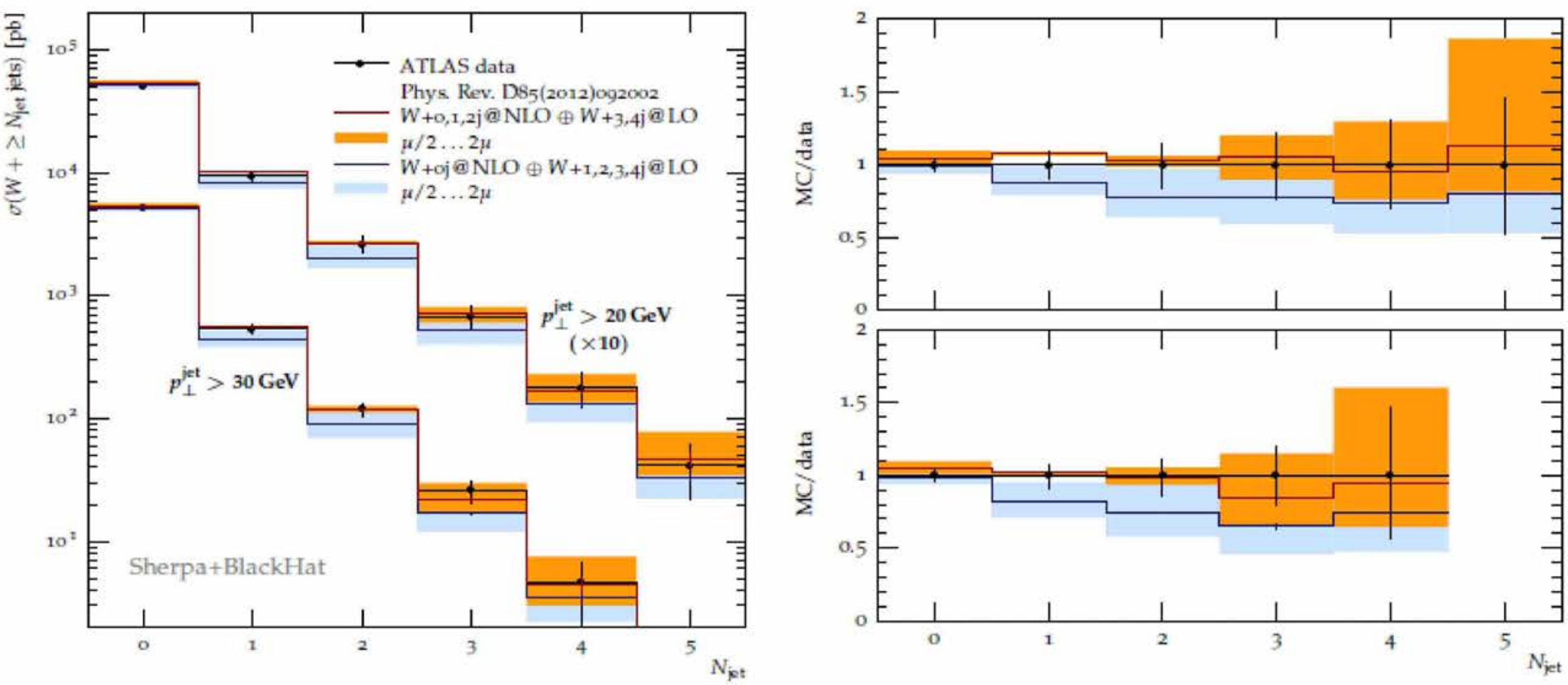
Lonnblad

Good description for high multiplicites

Merging in SHERPA

W+jets production at the LHC

[Hoeche,Krauss,Schoenherr,Siegert]



- MEPSatNLO with 0,1&2 jet PL at NLO plus 3&4 jet PL at LO
- vs 0 jet PL at NLO plus up to 4 jets at LO

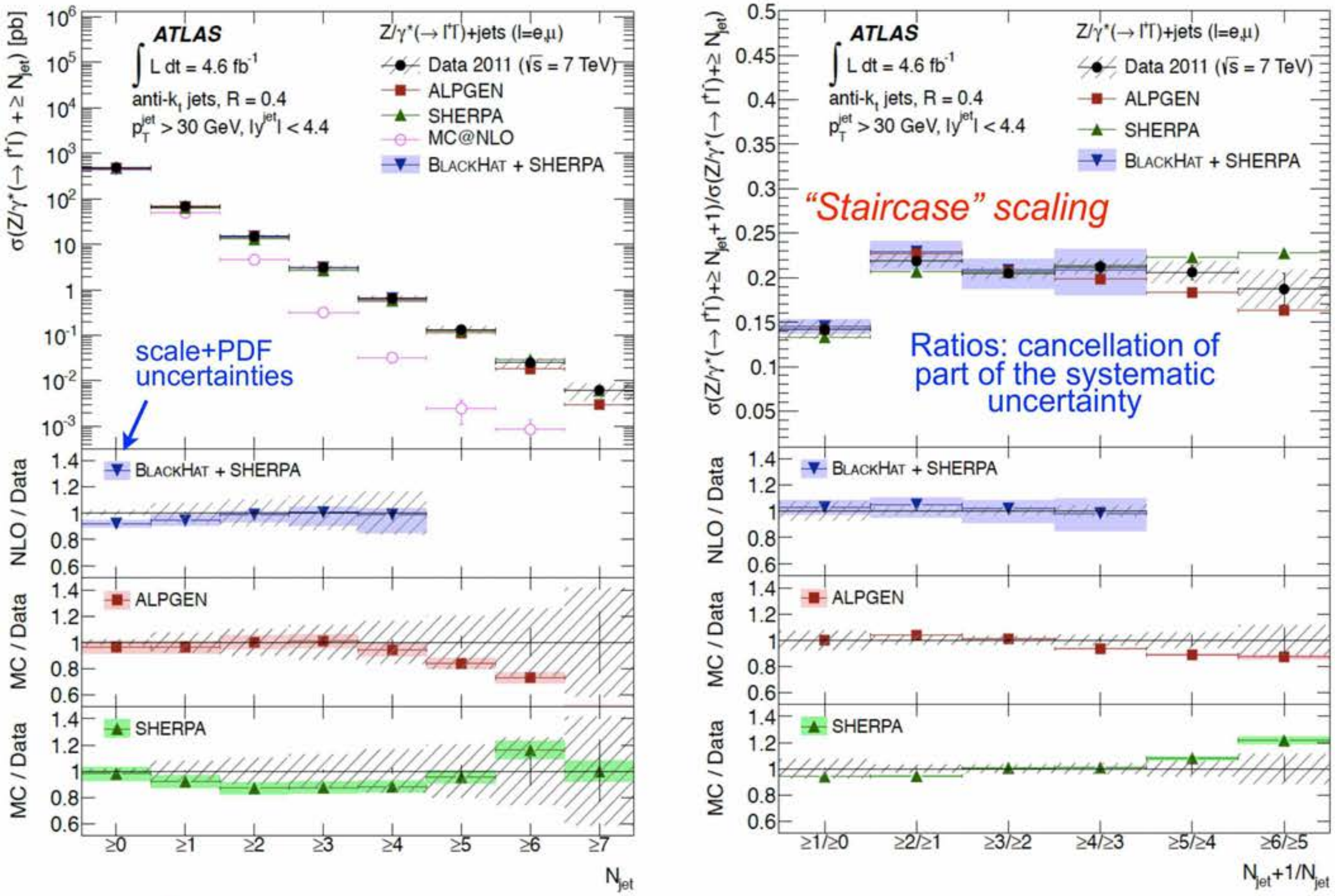
Andersen

Good description even for very high multiplicites

Z + jets - inclusive jet multiplicities

JHEP07(2013)032

- cross section for dressed electrons and particle jets in fiducial acceptance region
- normalized to inclusive cross section
  - cancel uncertainties on electron reco and integrated luminosity
- Jet energy scale is the dominant uncertainty
  - 20-30% effect in forward region

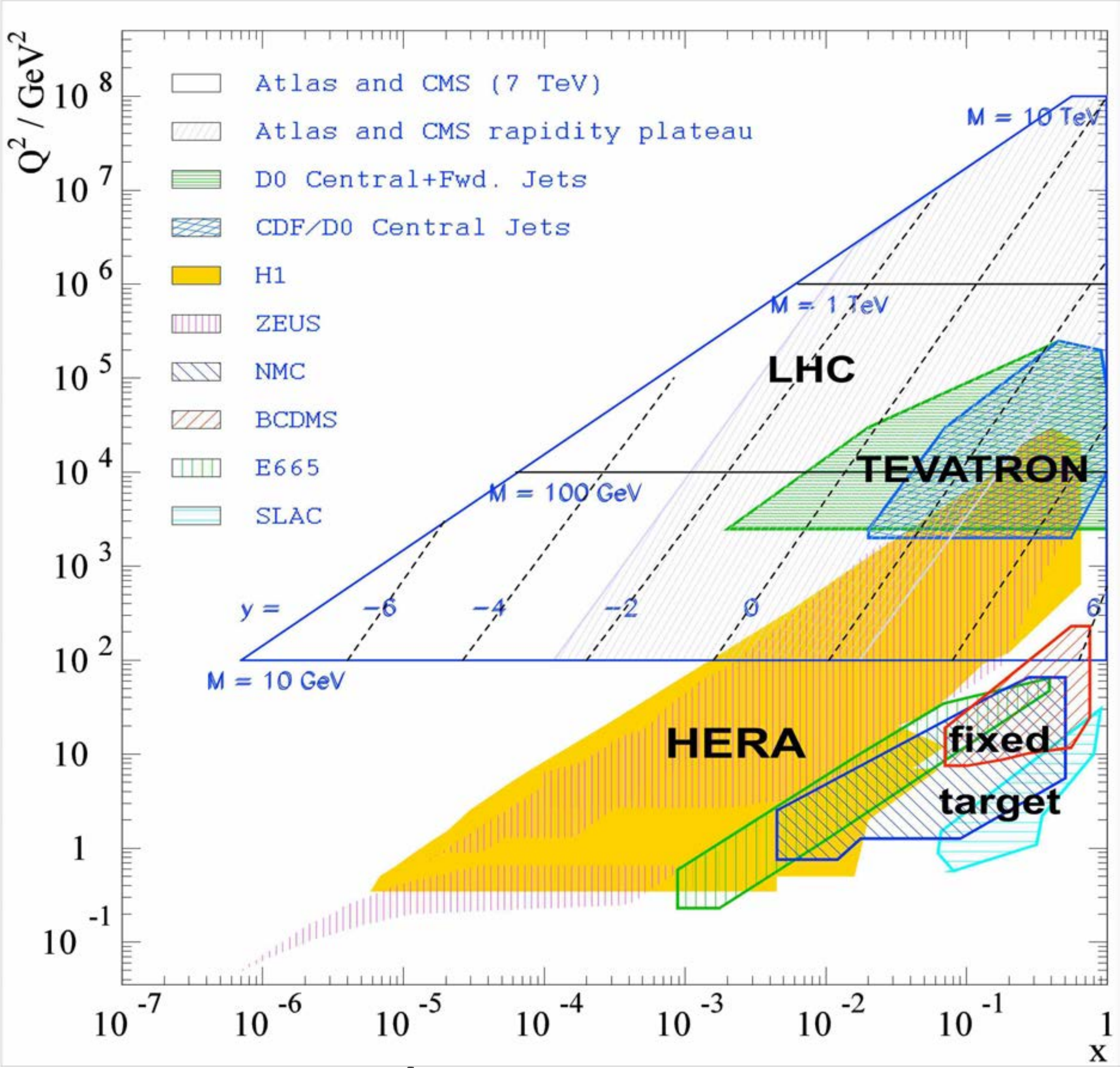


- BLACKHAT+SHERPA + CT10
- ALPGEN 2.13 + HERWIG +JIMMY + CTEQ6L1
- SHERPA 1.4.1 + MEnloPS + CT10

- Good description by fixed order NLO calculations and multi-leg MC + PS
  - MC@NLO agrees only for at most ≥ 1 jet (one parton from NLO real emission), otherwise HERWIG PS fails to model jet multiplicities

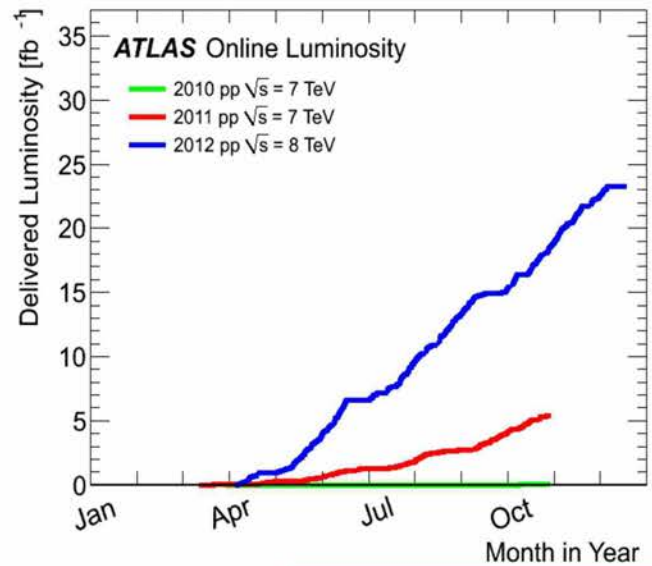
Lefebvre

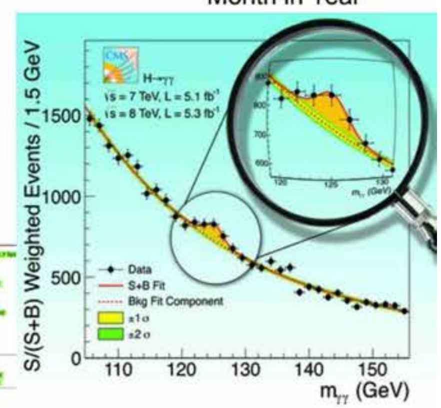
SEARCHES

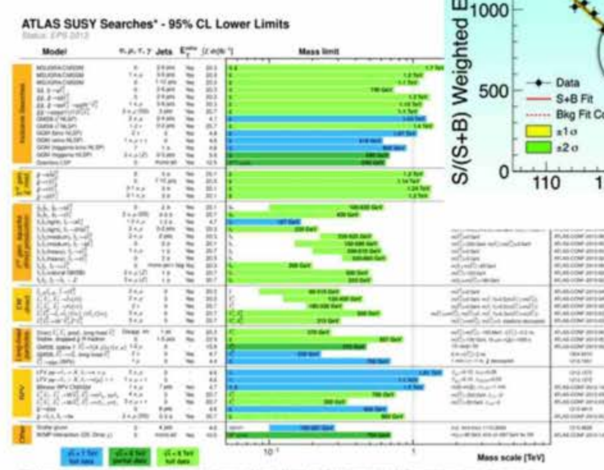

Atlas and CMS (7 TeV)
Atlas and CMS rapidity plateau
D0 Central+Fwd. Jets
CDF/D0 Central Jets
H1
ZEUS
NMC
BCDMS
E665
SLAC
M = 10 TeV
M = 1 TeV
LHC
TEVATRON
M = 100 GeV
y = −6 −4 −2 0 2 4 6
M = 10 GeV
HERA
fixed
target
Q^2 / GeV^2
10^{8}
10^{7}
10^{6}
10^{5}
10^{4}
10^{3}
10^{2}
10
1
10^{-1}
10^{-7} 10^{-6} 10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1} 1
x

LHC excellent tool for searches

- 2010-12 Successful running of LHC
  - 5 fb^{-1} data at 7 TeV
  - 23 fb^{-1} data at 8 TeV
- Discovery machine
  - Discovery of a Higgs Boson
  - Wide range of SUSY searches
  - Test of many exotic models
- Experimental results in Searches
  - Depend on QCD
  - Experimental handle
  - The use of predictions



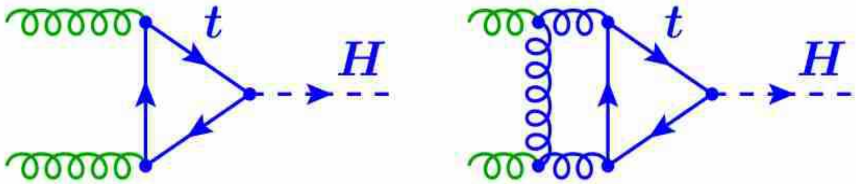




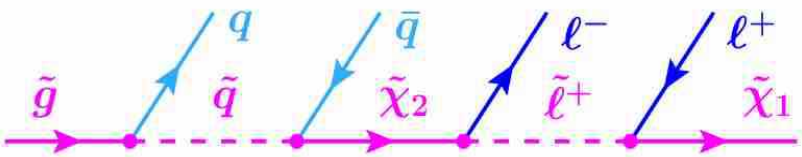
Kuhl

QCD in Higgs and BSM

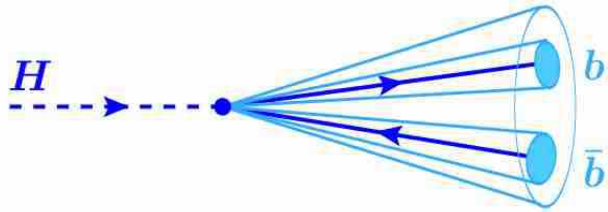
QCD is everywhere



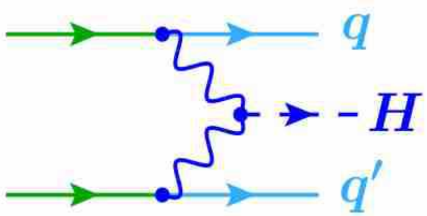
- Inclusive production cross sections
  - Sizable QCD corrections in colored production processes
  - PDFs



- Decays
  - Jets from decays (BSM cascades)
  - Boosted topologies (boosted tops, $H \to b\bar{b}$)



- In association
  - Additional jets from ISR
  - Weak boson fusion processes



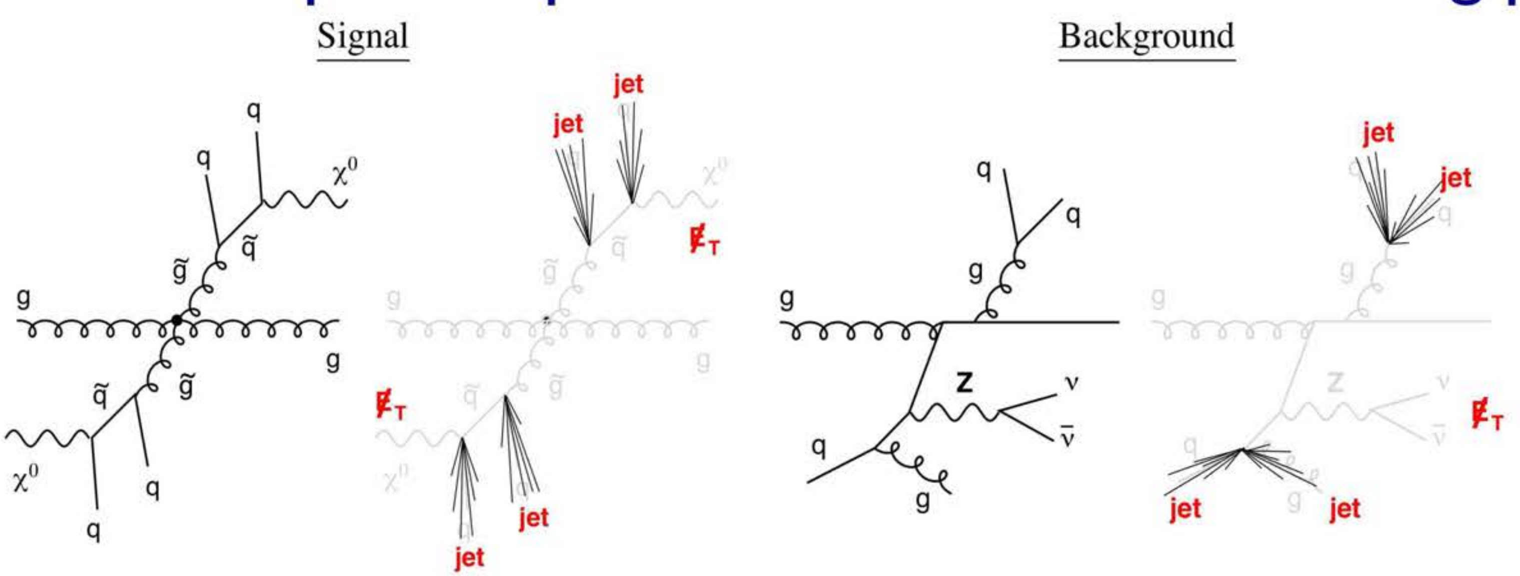
- SM backgrounds
  - QCD jet production, $W/Z+$ jets, top decays
  - Signal-background interference effects ($H \to \gamma\gamma/ZZ/WW$)

Tackmann

You need QCD for your searches

Multi-particle production at LHC

- LHC brings new frontiers in energy and luminosity
- Production of short-lived heavy states (Higgs, top, SUSY…)
  - detected through their decay products
  - yield multi-particle final states involving jets, leptons, γ , $\not{E}_T$
- Search for new effects in multi-particle final states
- Need precise predictions for hard scattering processes

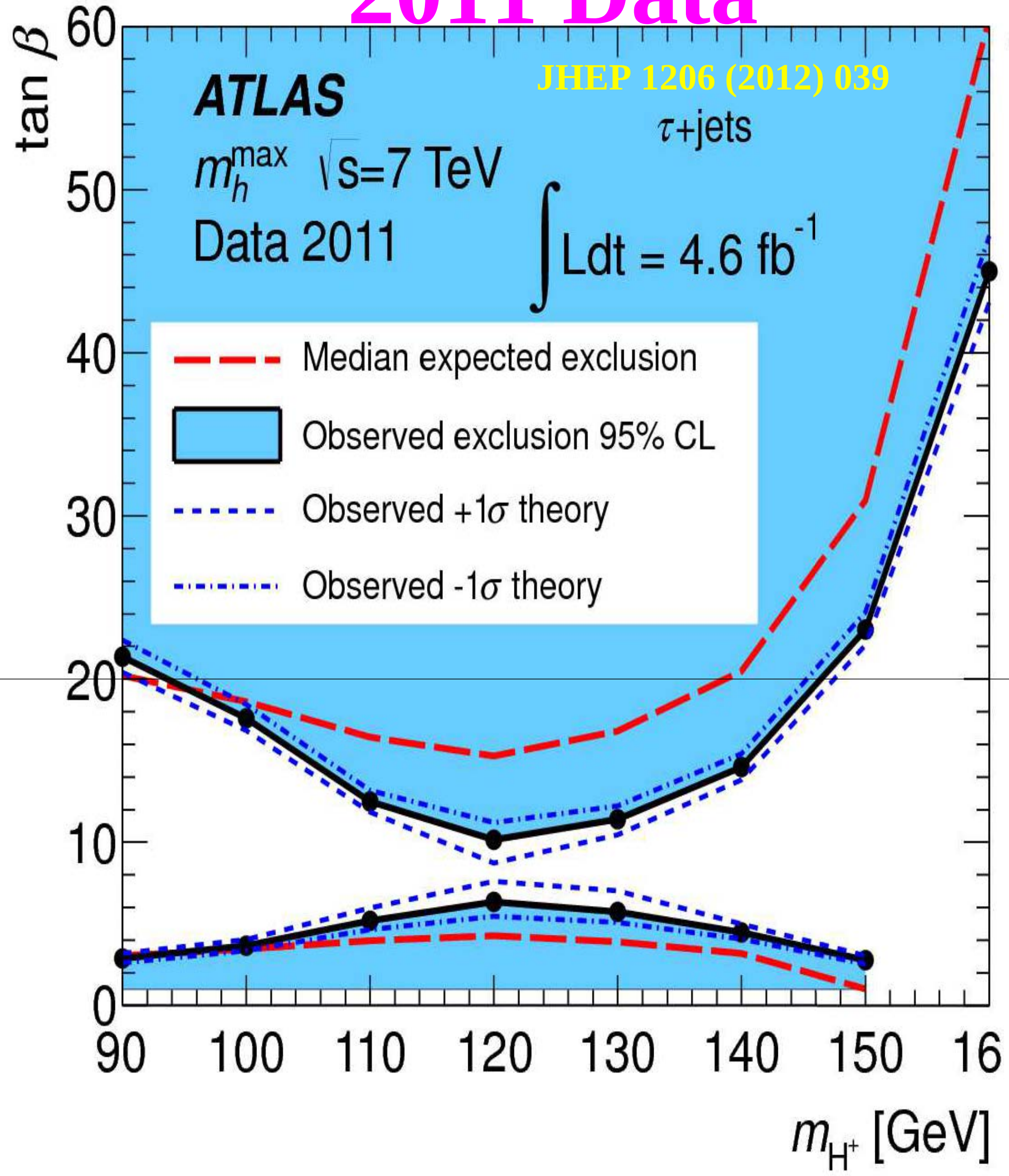


Example: SUSY signature 4j + $\not{E}_T$

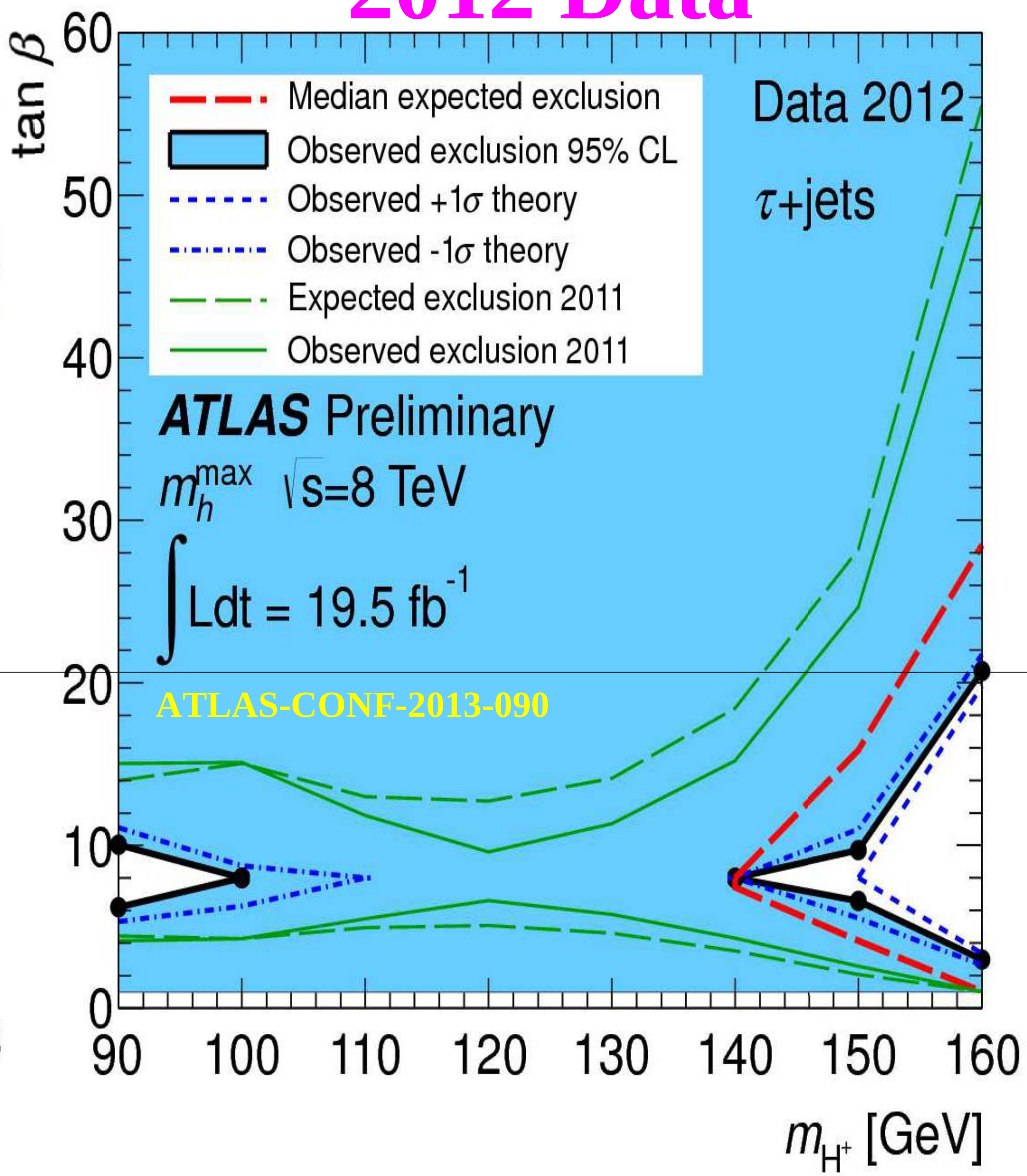
Gehrmann

Parameter Space for Charged Higgs

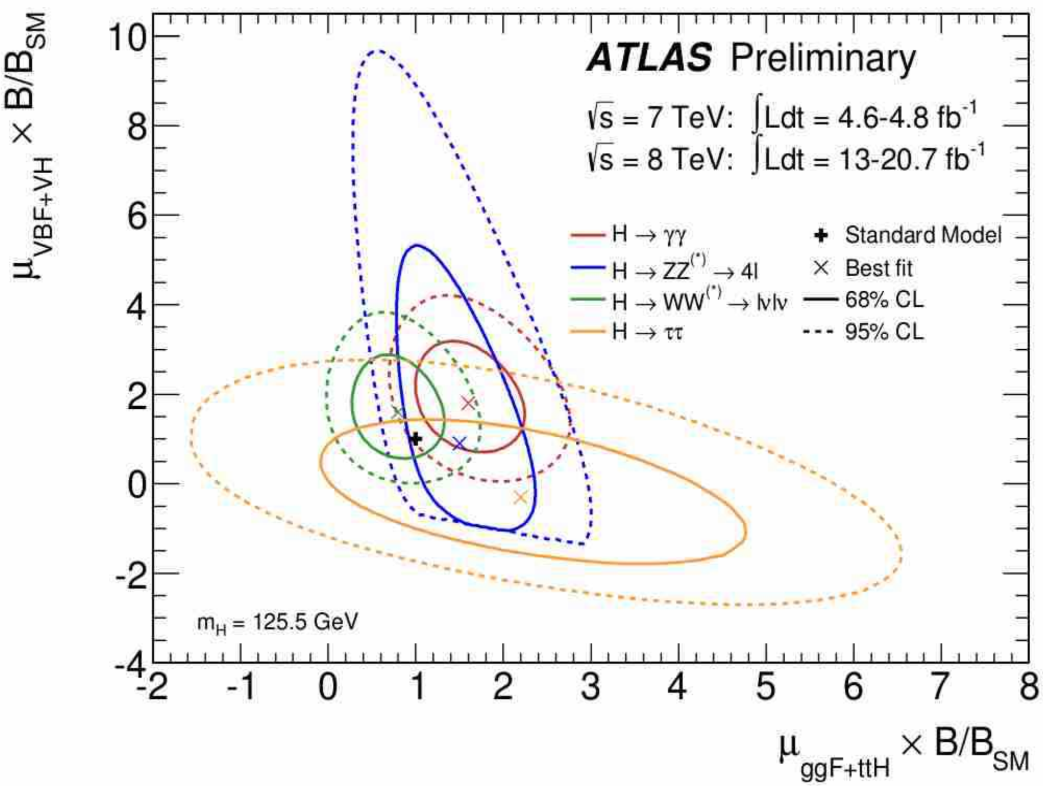
2011 Data

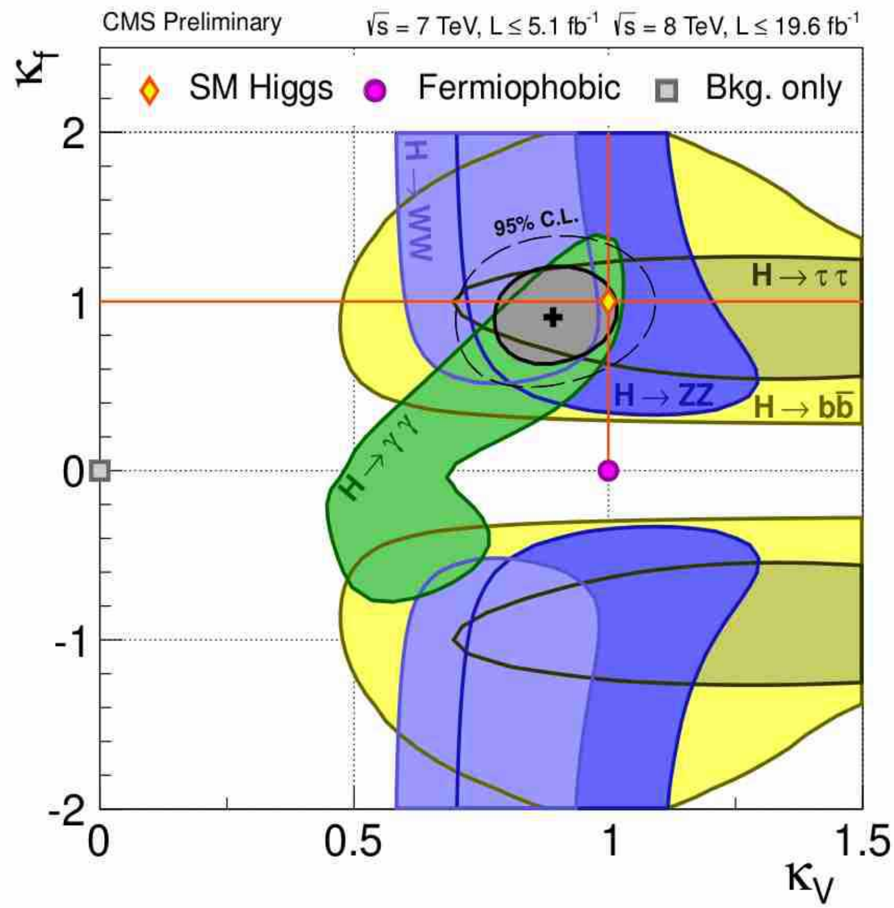


2012 Data



Determining Higgs Couplings





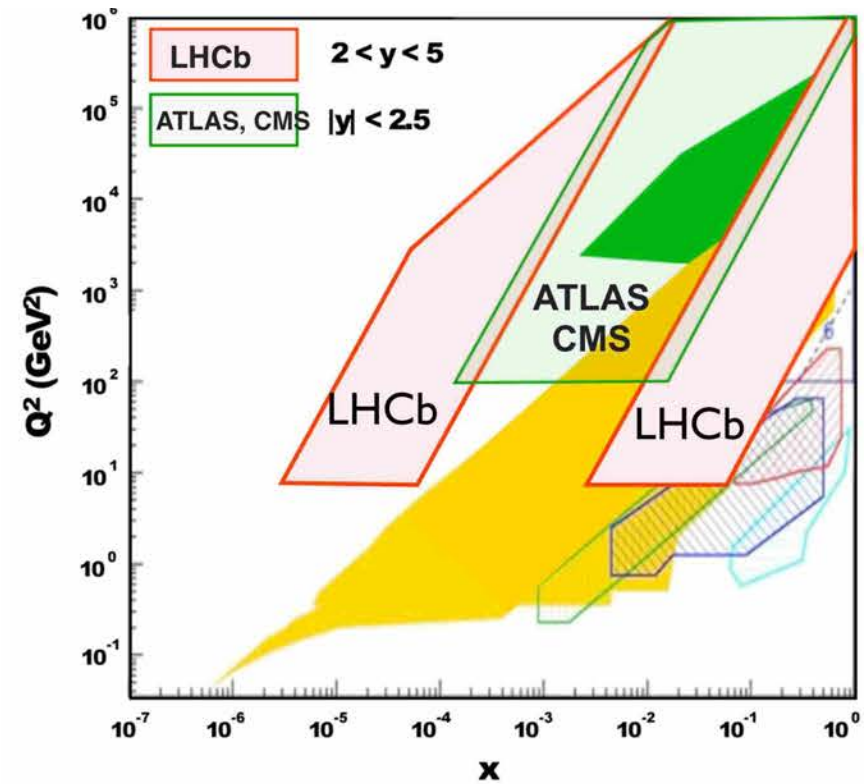
So far consistent with the SM Higgs

- Every measurement is also an indirect search (not just Higgs, also top, flavor, ...)

⇒ Discovering BSM effects in Higgs couplings at the few to $\mathcal{O}(10\%)$ level requires detailed and precise control of QCD effects at the same level including reliable theory uncertainties and correlations.

Tackmann

Resummation & Small x



Large kinematic ranges → disparate scales → Large Logs

Multi-scale QCD Processes

♣ Part of the effects are "universal"

$\gamma \simeq$

♣ Part of t

↪

⇒ L

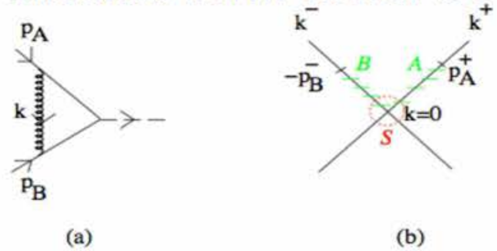
Hautmann

F. Hautmann: QCD@LHC 20

TMD evolution equations

Examples:

- Sudakov form factor S:

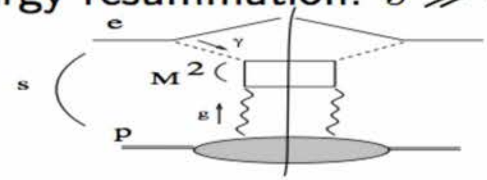


▷ entering Drell-Yan production, W-boson $p_\perp$ distribution, . . .

$\Rightarrow \partial S/\partial\eta = K \otimes S$ CSS evolution equations [Collins-Soper-Sterman]

↖ resums $\alpha_s^n \ln^m M/p_T$

- High-energy resummation: $s \gg M^2 \gg \Lambda^2_{QCD}$



◇ energy evolution: BFKL equation [Balitsky-Fadin-Kuraev-Lipatov]

↪ corrections down by $1/\ln s$ rather than $1/M$

CCFM equation is TMD branching equation which contains both Sudakov physics and BFKL physics (see later)

F. Hautmann: QCD@LHC 2013, DESY

Higgs PT Resummation known to high order

Resummation Cartoon

Systematic reorganization of perturbative series

$\hat{\sigma} \sim c_{00} +$

$+\alpha_s \big(c_{12} \log^2 (1\text{-}z) + c_{11} \log (1\text{-}z) + c_{10} \big)$ ← NLO

$+\alpha_s^2 \big(c_{24} \log^4 (1\text{-}z) + c_{23} \log^3 (1\text{-}$ …

$\alpha_s^n \log^{2n}(1\text{-}z)$ $\alpha_s^n \log^{2n\text{-}}$ …

Factorization: space of Melin moment…

$\hat{\sigma}^{(N)} \sim \mathcal{C}(\alpha_s) \exp\left[L g_1(\alpha\right.$ …

…L: $\alpha_s^n \log$ …

Kulesza

A. Kulesza, Resummation @ LHC

Lots of practice on W/Z

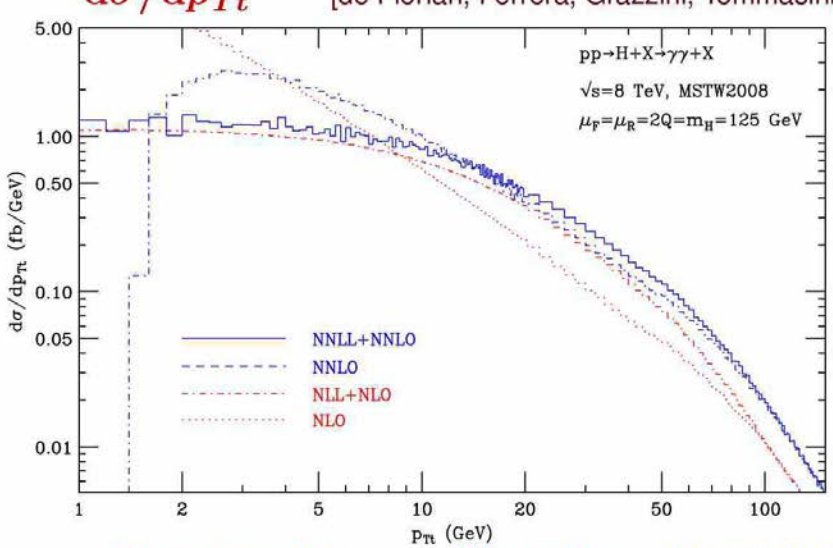
Resummation for Higgs p_T

Resummation for p_T^{Higgs} is known to NNLL+NNLO

[Bozzi, Catani, de Florian, Grazzini; Cao, Chen, Schmidt, Yuan; Becher, Neubert; Chiu et al.]

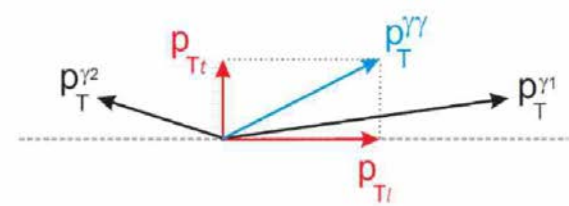
- NNLL resummation using classical p_T resummation or via RGE in SCET
- (N)NLO relative to underlying $gg \to H$ process

$d\sigma / dp_{Tt}$ [de Florian, Ferrera, Grazzini, Tommasini]



Resummation Transition Fixed Order

For $H \to \gamma\gamma$: $\mathcal{T} \equiv p_{Tt}$



⇒ Closely related to $p_T^{\gamma\gamma} \equiv p_T^{\mathrm{Higgs}}$ but depends on precise Higgs decay kinematics

Frank Tackmann (DESY) QCD in Higgs and BSM

Tackmann

Challenging to describe throughout full kinematic region

Rapidity Gap cross section

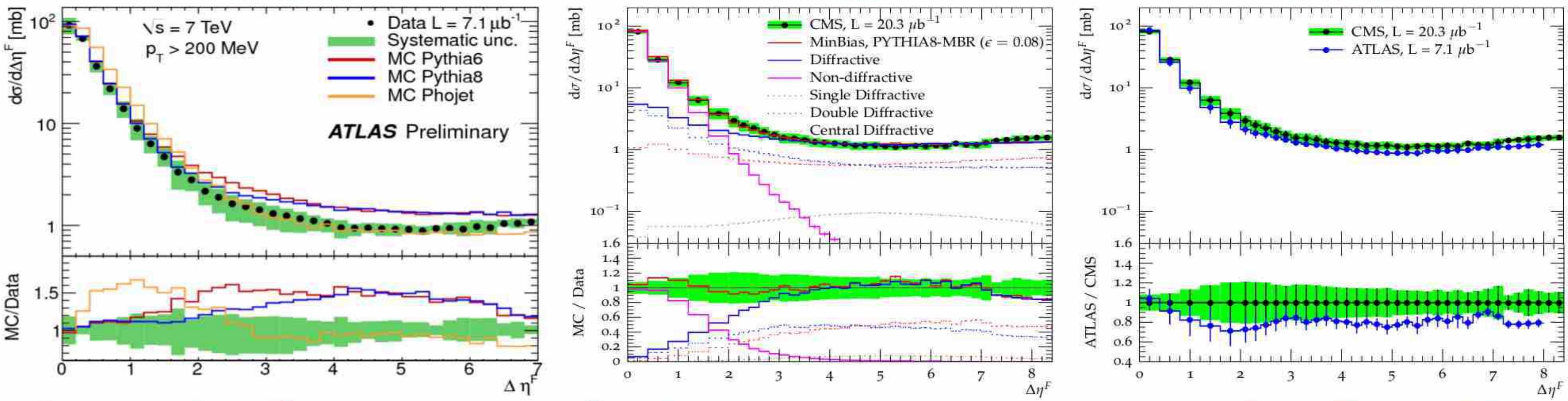
Eur. Phys. J. C72 (2012) 1926 & CMS-PAS-FSQ-12-005

Forward rapidity gap $\Delta\eta^F$: largest empty η region, starting at the edge of the detector

Inclusive measurement - no separation of diffraction

Same hadron level definition ATLAS-CMS: gap defined by absence of particle with $p_T > 200$ MeV

ATLAS | **CMS** | **Comparison**



Evidence for diffraction at high $\Delta\eta^F$: ND exponentially suppressed - plateau from SD and DD

Diffractive plateau $\sim$ 1 mb / unit of gap size

Sensitivity to diffractive models: PYTHIA8-MBR with $\alpha_P(0) = 1.08$ gives the best description

Phojet in good agreement at high $\Delta\eta^F$ but overestimates data at low $\Delta\eta^F$

Agreement ATLAS-CMS within uncertainties - CMS extends ATLAS by 0.4 unit of gap size

Roland

… lots of activity

WHAT I DIDN'T TALK ABOUT (INCOMPLETE LIST)

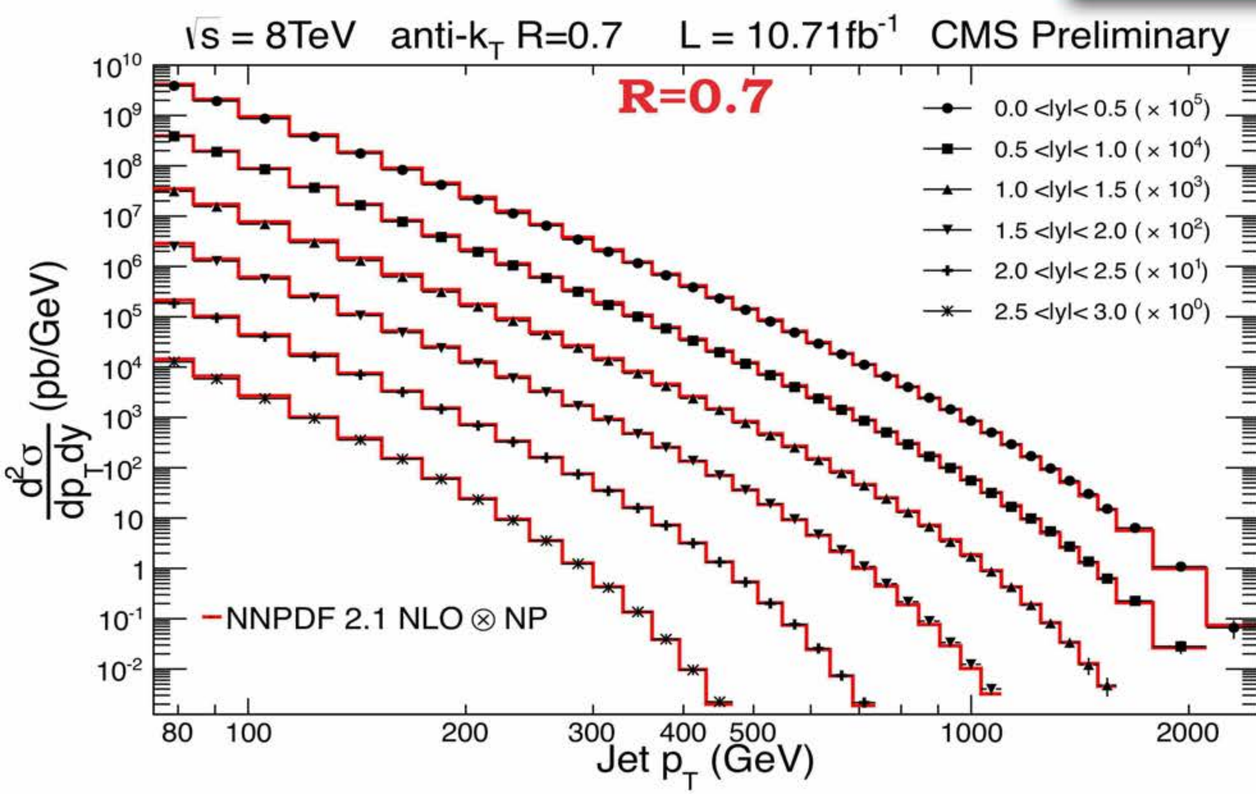
- Next-to-eikonal exponentiation *[Laenen, Magnea, Stavenga, White'10]*
- Webs *[Gardi, White'11] [Gardi, Smillie, White'11'13]*
- Collinear factorization breaking *[Catani, de Florian, Rodrigo'11][Forshaw, Seymour, Siódmok]*
- IR singularities in the high-energy limit *[del Duca, Duhr, Gardi, Magnea, White'11-'12]*
- Effects due to final state interactions *[Mitov, Sterman'12]*
- Constructing approximate cross sections from threshold and small-x resummation *[Moch, Uwer, Vogt'12] [Kawamura, Lo Presti, Moch, Vogt'12] [Ball, Bonvini, Forte, Marzani, Ridolfi'13]*
- Collinear anomaly and the generation of non-perturbative scale (DY, Higgs p_T spectrum) *[Becher, Neubert, Wilhelm'11-12]*
- Understanding of ambiguities of the DQCD approach due to various resummation prescriptions: MP vs Borel resummation *[Bonvini, Forte, Ridolfi'12]*
- Resummation for new variables a_T and ϕ^* in DY *[Banfi, Dasgupta, Marzani, Tomlison'12]*
- Resummation for photon, W, Z at large p_T *[Kidonakis, Gonzalves'12][Becher, Schwartz'10][Becher, Lorentzen, Schwartz'12]*
- Progress towards NNLL in single-particle inclusive hadroproduction *[Catani, Grazzini, Torre'13]*
- FONLL results for open charm and bottom production *[Cacciari, Frixione, Mangano, Nason, Ridolfi'12]*
- MPI and resummation *[Diehl, Ostermaier, Schaefer'11][, [Diehl, lKasemets'12][Manohar, Waalewijn'12]*
- From resummation to MC events: GENEVA *[Alioli, Bauer, Berggren, Hornig, Tackmann, Vermilion, Walsh, Zuberi]*
- Resummation of logs of isolation cone sizes for prompt photons *[Catani, Finntanaz, Guillet, Pilon'13]*

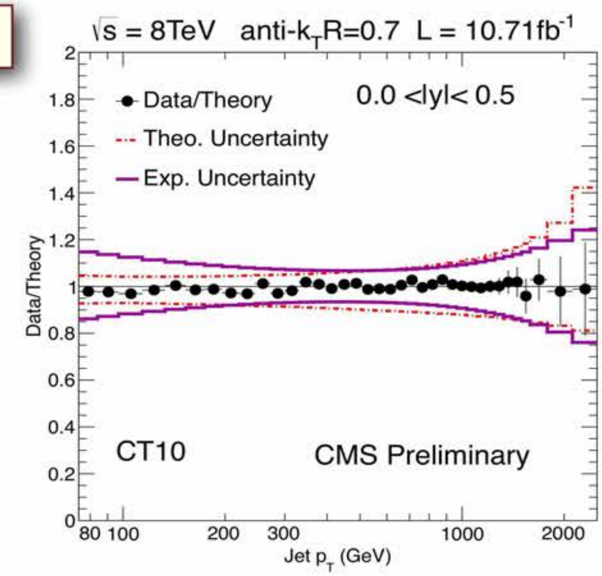
Kulesza

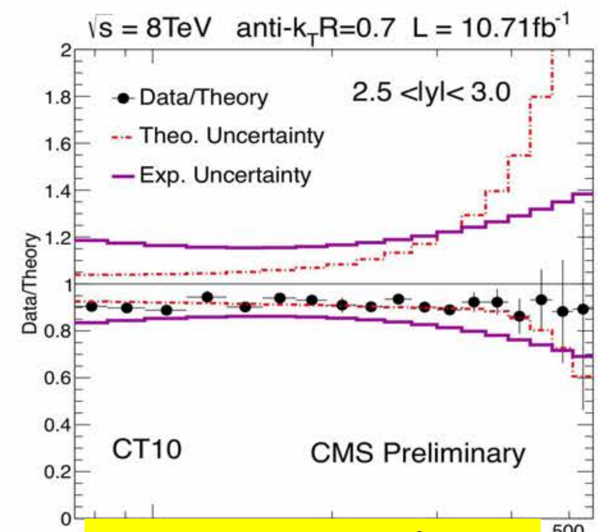
JETS

Inclusive jet cross sections @ 8 TeV

CMS-PAS-SMP-12-012







- first (preliminary) measurement @ 8 TeV up to |y| = 3.0
  - ~half 2012 dataset
- experimental uncertainties at high p_T smaller than theoretical
  - potential for PDF constrains
- NLO pQCD predictions compatible with data

Kousouris

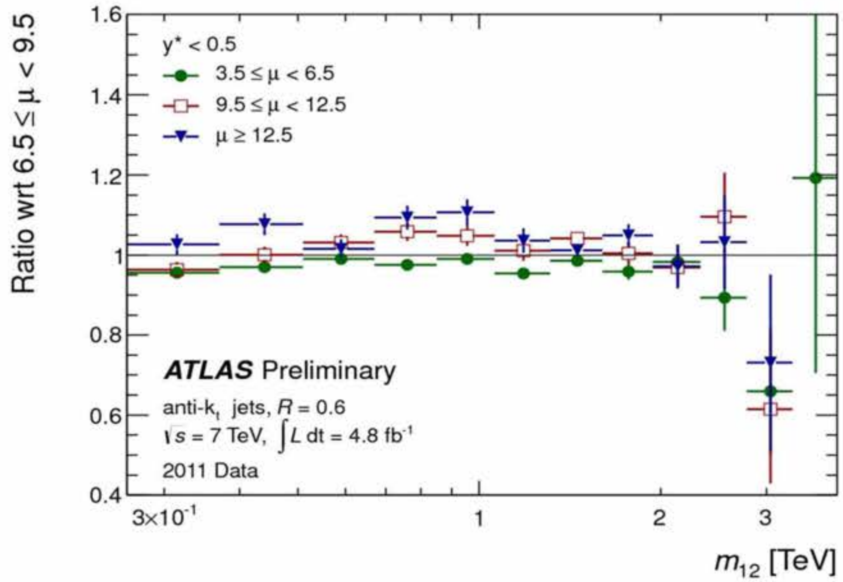
Also good agreement

Dijet Cross Sections at $\sqrt{s}$ = 7 TeV

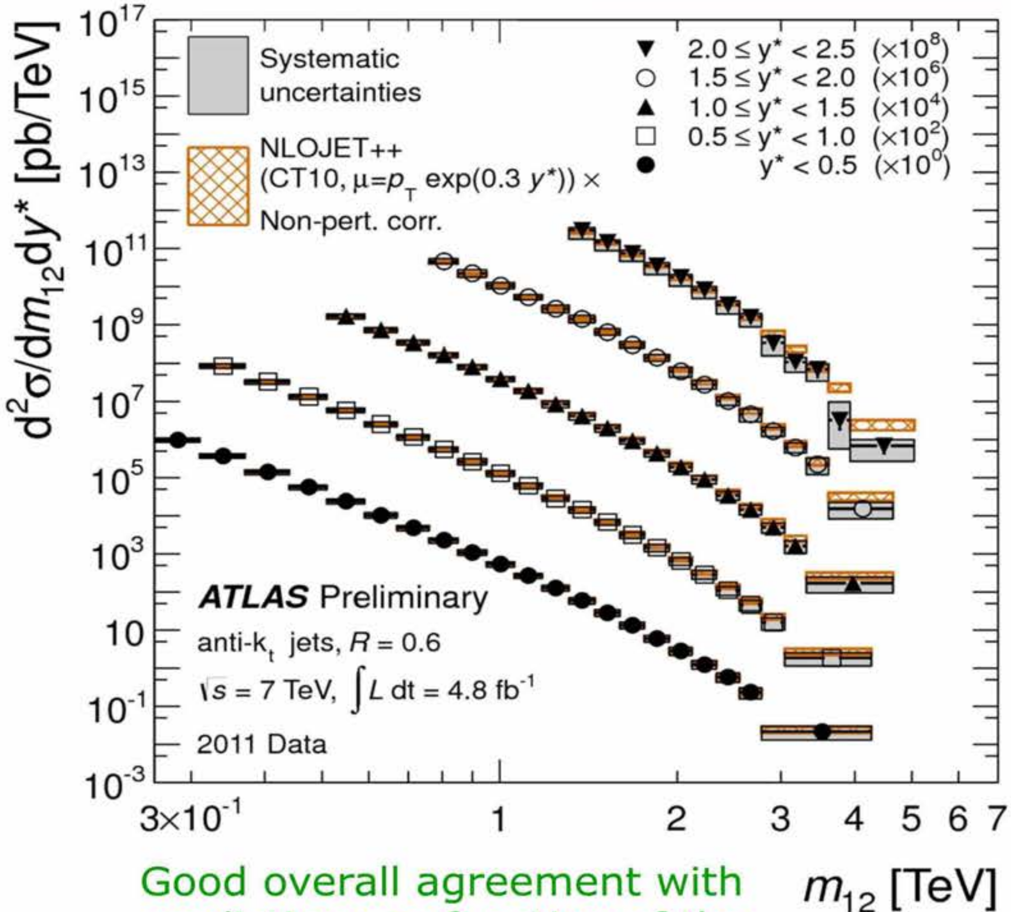
Event selection: leading jet with p_T>100 GeV, sub-leading jet with p_T>50 GeV both in the central region with |y|<2.8

$y^* = \frac{1}{2}|y_1 - y_2|$

Since the average number of interactions per bunch crossing μ is large, it is important to check the applied correction through the ratio of cross sections:



5-7% consistent between various μ ranges.



Good overall agreement with predictions as function of the invariant mass up to **~4 TeV**

Corriveau

JET SUBSTRUCTURE

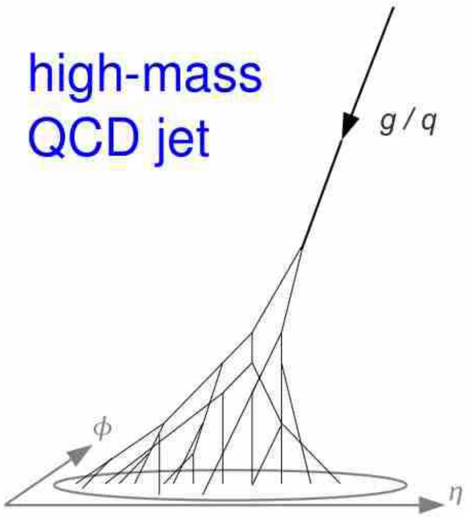
Use the jet structure to filter background

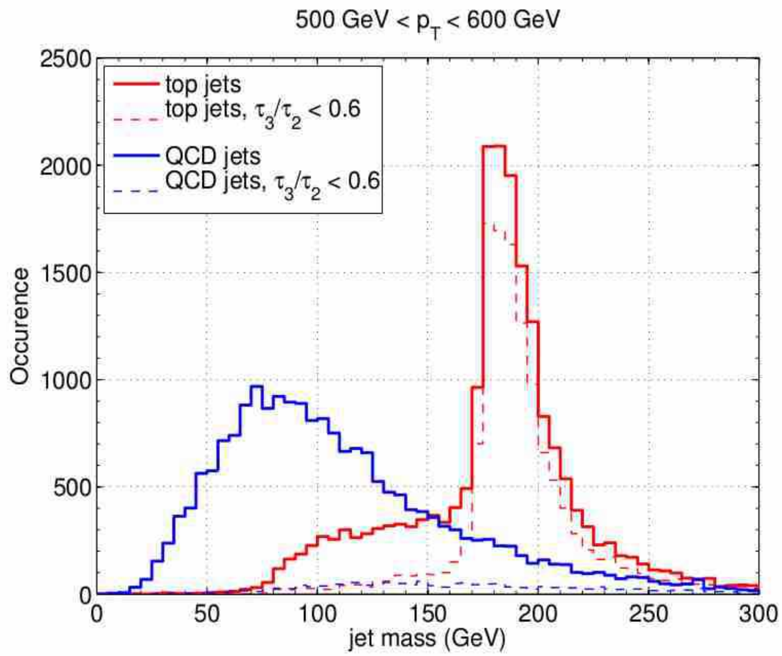
Boosting Searches with Jet Substructure

For boosted tops, e.g. from $Z' \to t\bar{t}$, jets from top decay are very close

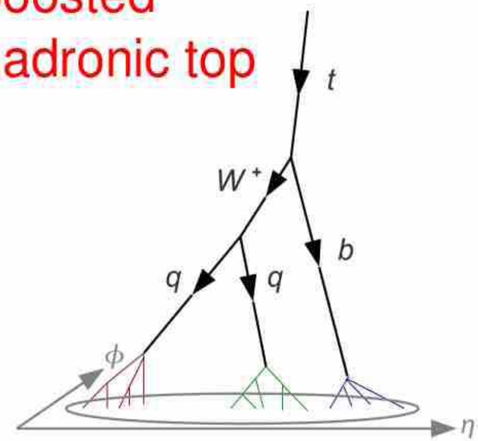
- Looking for a for single top-jet with large R becomes more efficient than looking for 3 separated small-R jets $\longrightarrow$ need substructure of large jet to discriminate

high-mass QCD jet





boosted hadronic top



ATLAS and CMS are starting to use boosted analyses in searches

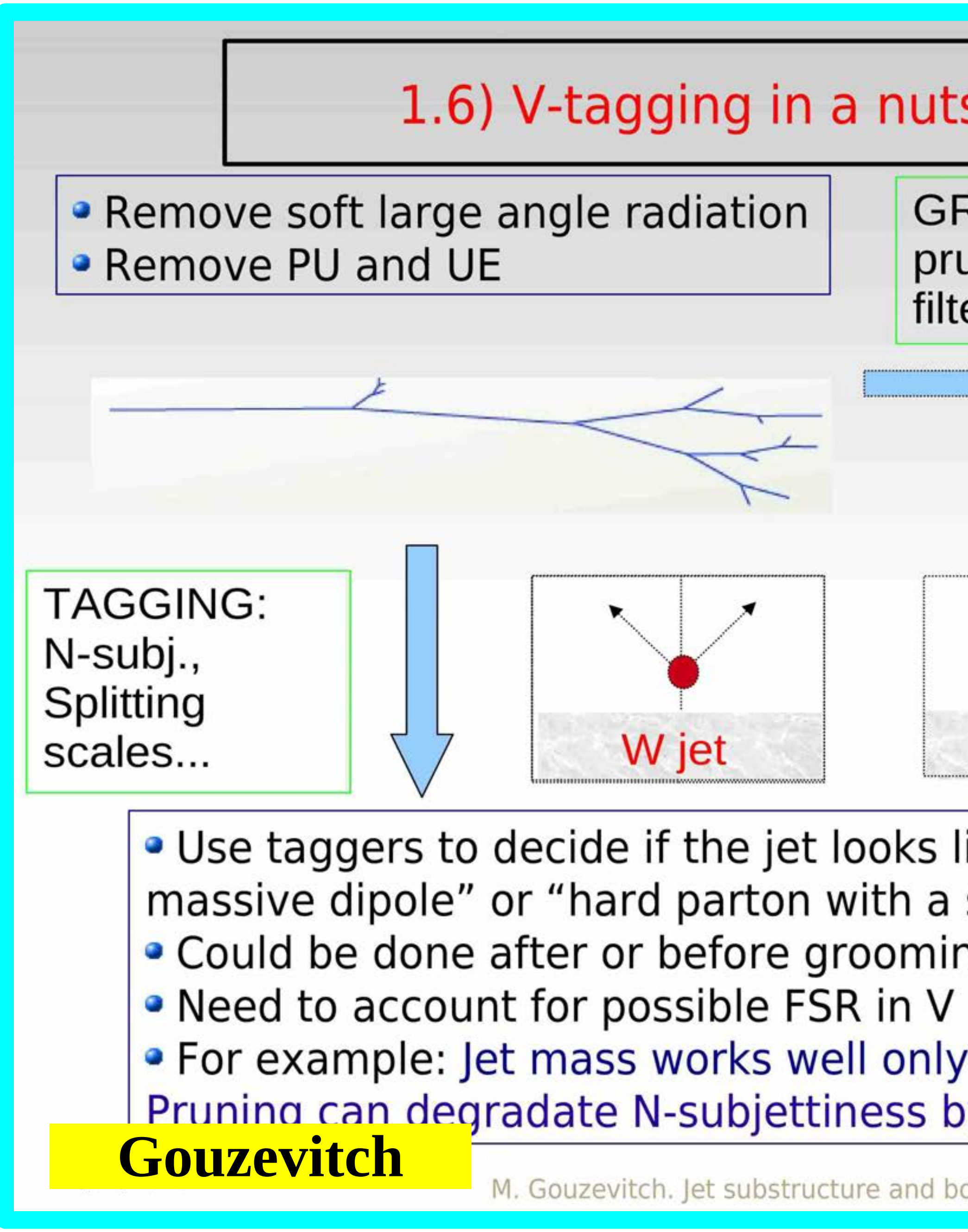
[see yesterday's talks by Frank Merritt and Aniello Spiezia]

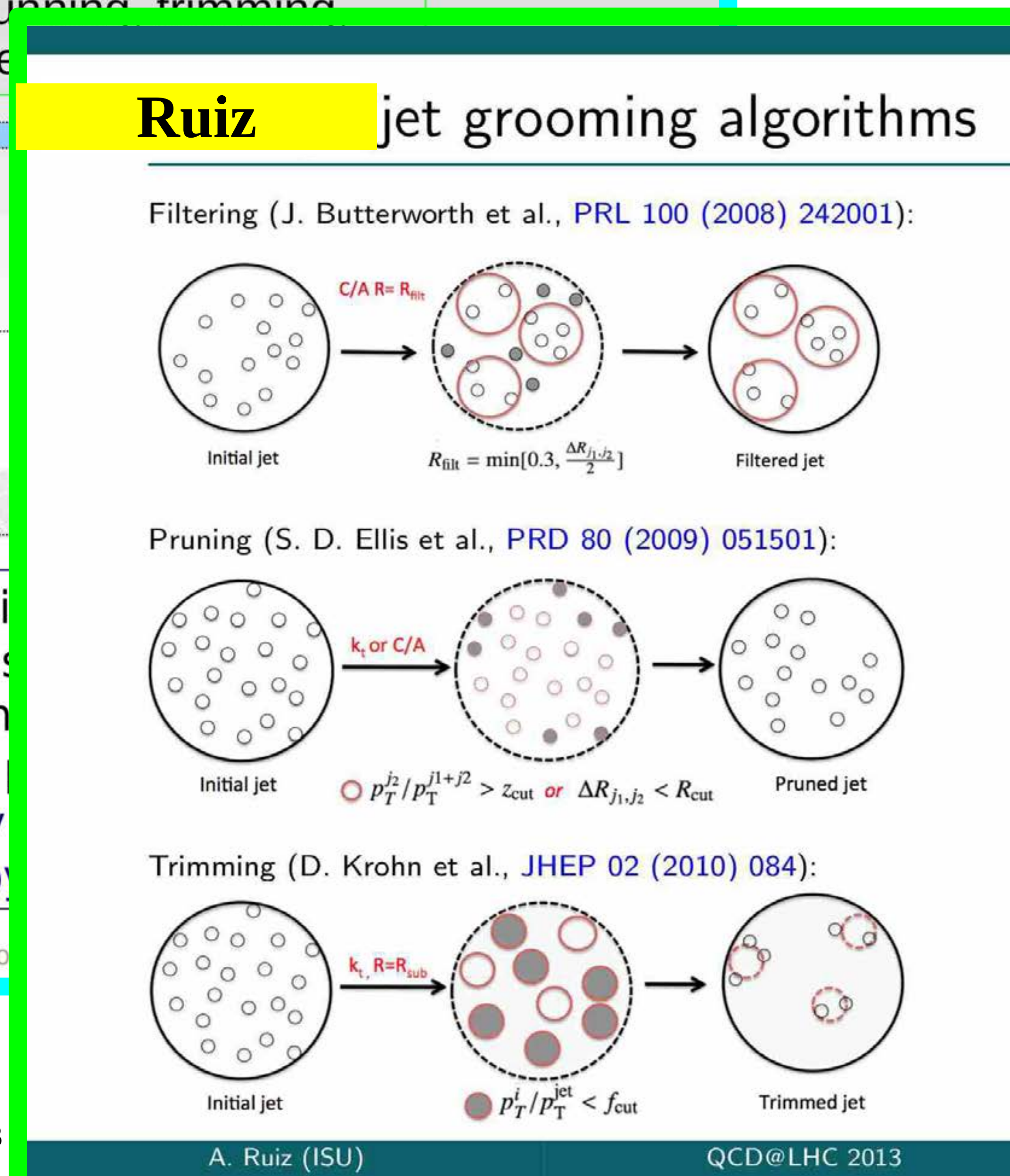
- Essential to extend reach to highest p_T and $m_{t\bar{t}}$, even more so for Run-II

$\Rightarrow$ While there has been much progress on the theory side, we have really just scratched the surface

Tackmann

Recent activity is extensive

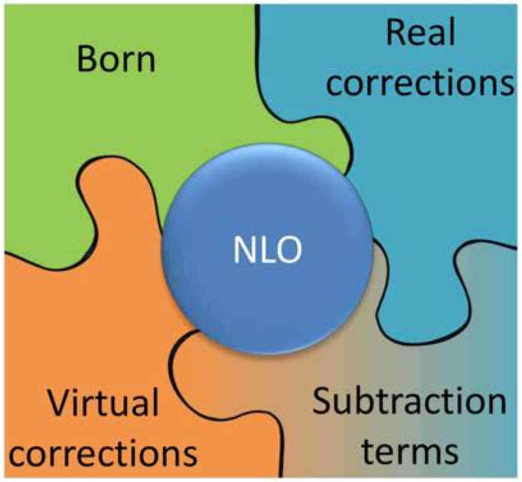




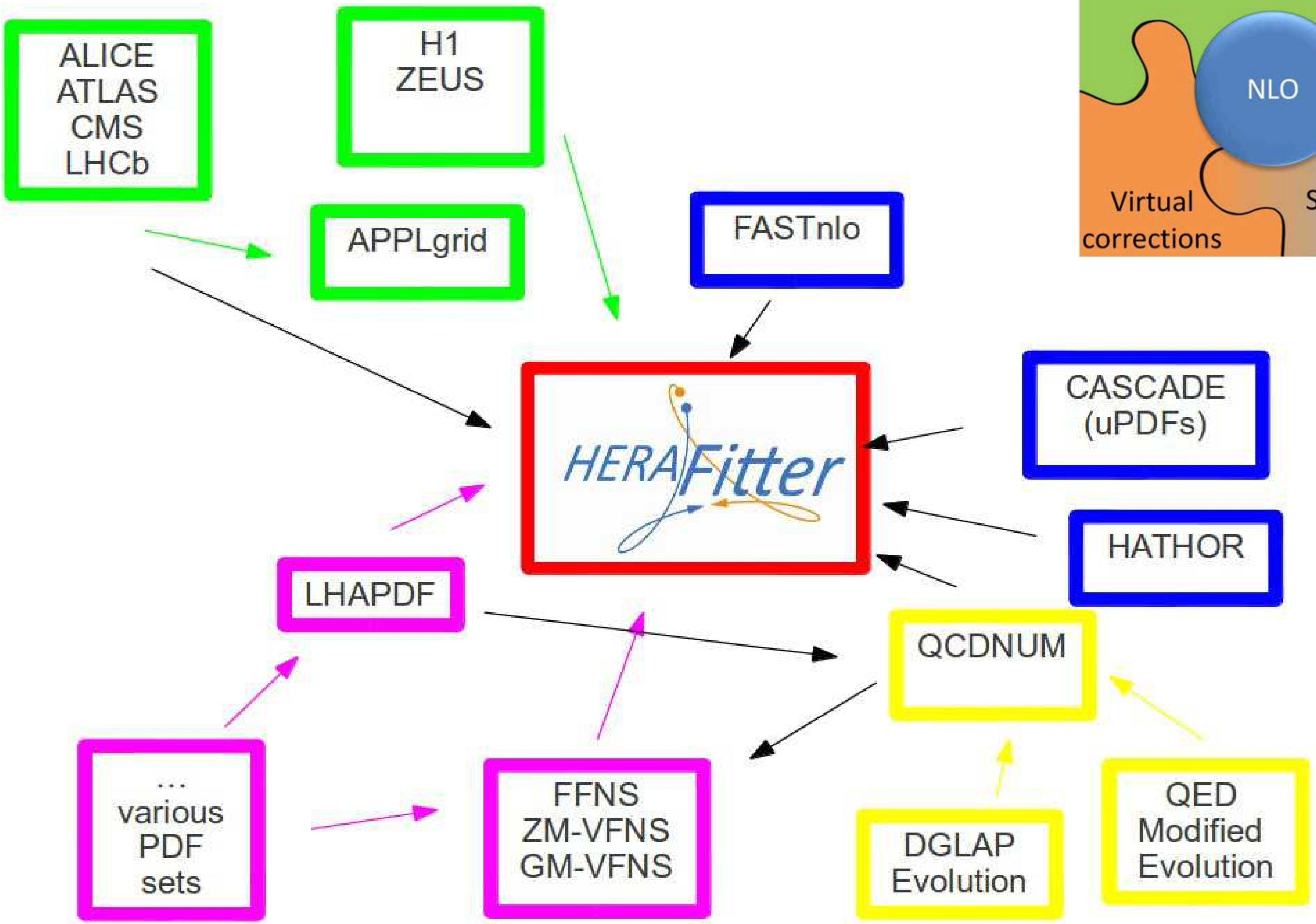
PDF_4LHC

$PDF_{(from)}LHC$

HERA FITTER

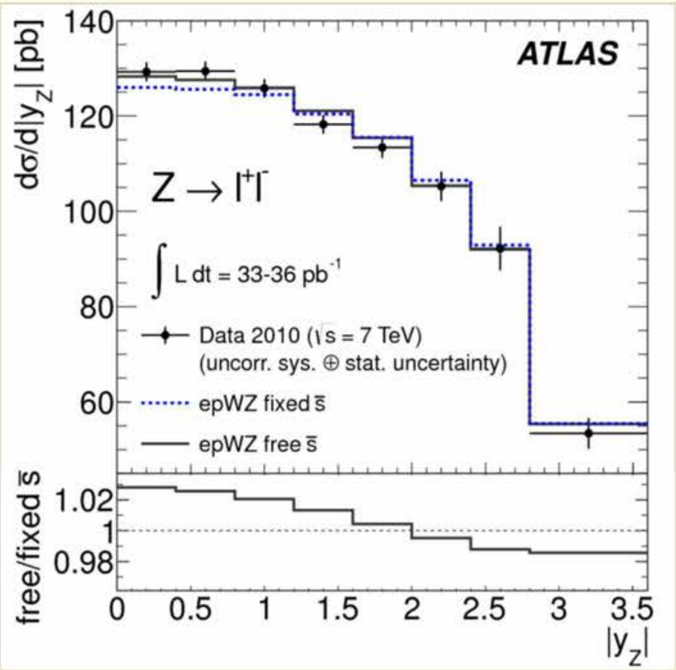


Born
Real corrections
NLO
Virtual corrections
Subtraction terms



ALICE
ATLAS
CMS
LHCb
H1
ZEUS
APPLgrid
FASTnlo
HERAFitter
CASCADE
(uPDFs)
HATHOR
LHAPDF
QCDNUM
...
various
PDF
sets
FFNS
ZM-VFNS
GM-VFNS
DGLAP
Evolution
QED
Modified
Evolution

s(x) from LHC W/Z:



YES WE CAN: ATLAS Phys Rev Lett 109(2012)012001

NNLO PDF fits to the ATLAS W,Z data plus HERA data (using HERAfitter) are shown for two assumptions about strangeness: s/d = 0.5 fixed and $s/d = r_s\,(1-x)^{(Cs-Cd)}$ – fitted.

The fit gives $s/d = r_s = 1.0 \pm 0.25$

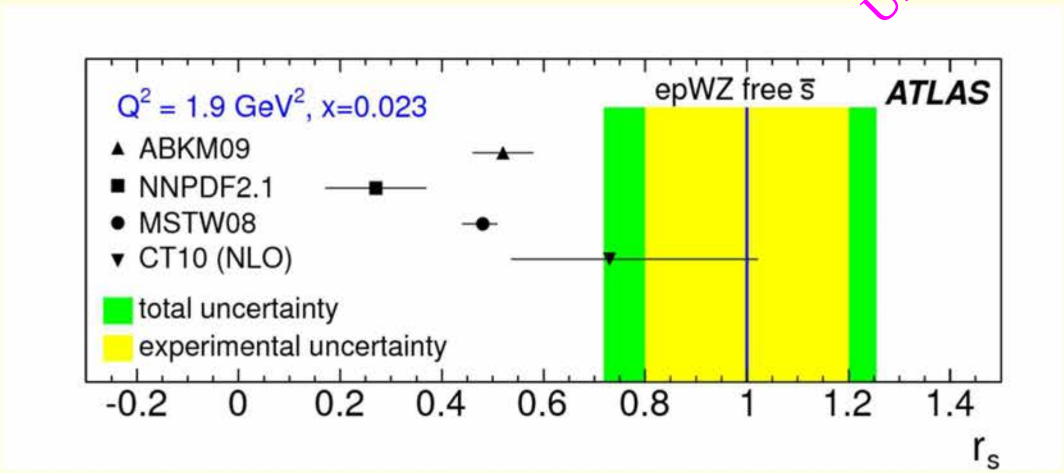
$$r_s = 1.00 \pm 0.20_{exp} \pm 0.07_{mod}\ {}^{+0.10}/_{-0.15\ par}\ {}^{+0.06}/_{-0.07\ \alpha s} \pm 0.08_{th}$$

The experimental accuracy of the result depends on the shape of the Z spectrum and on its correlation to the W spectra, which fixes the normalisation.

Using HERA Fitter

This result indicates enhanced strangeness in agreement with the CT10 predictions at x~0.01 - which is the kinematic region probed by LHC data.

In fact the ATLAS 'epWZ' fit has even more strangeness than CT10

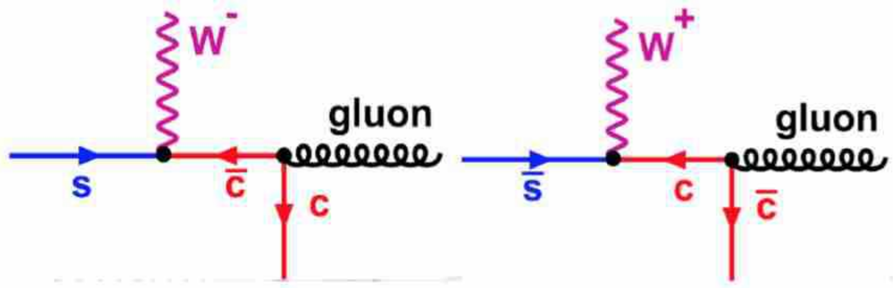


Cooper-Sarkar

Wc Production can also constrain s(x)

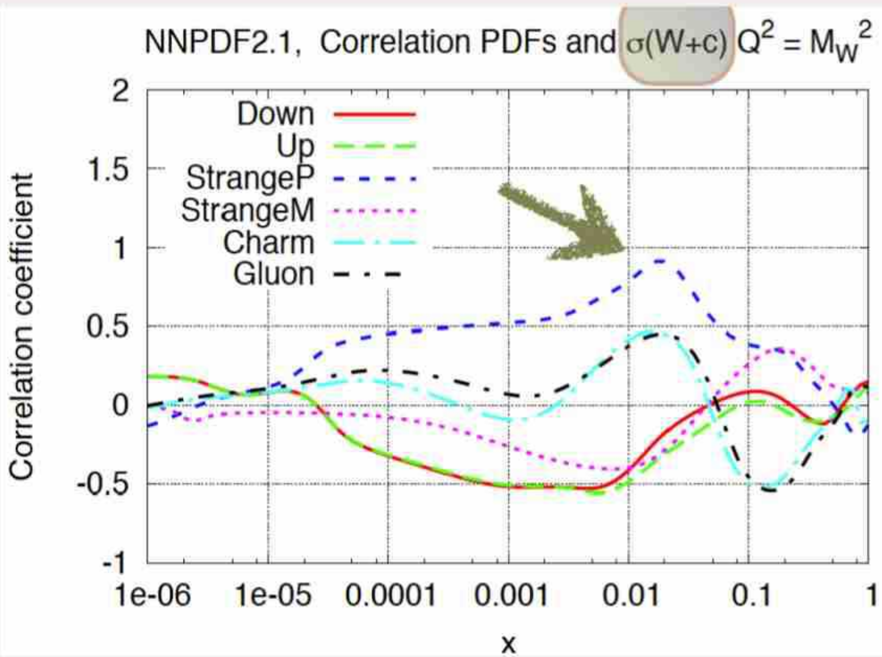
Improves over Tevatron and pre-LHC studies

W+charm: a test of the strange-quark content of the proton



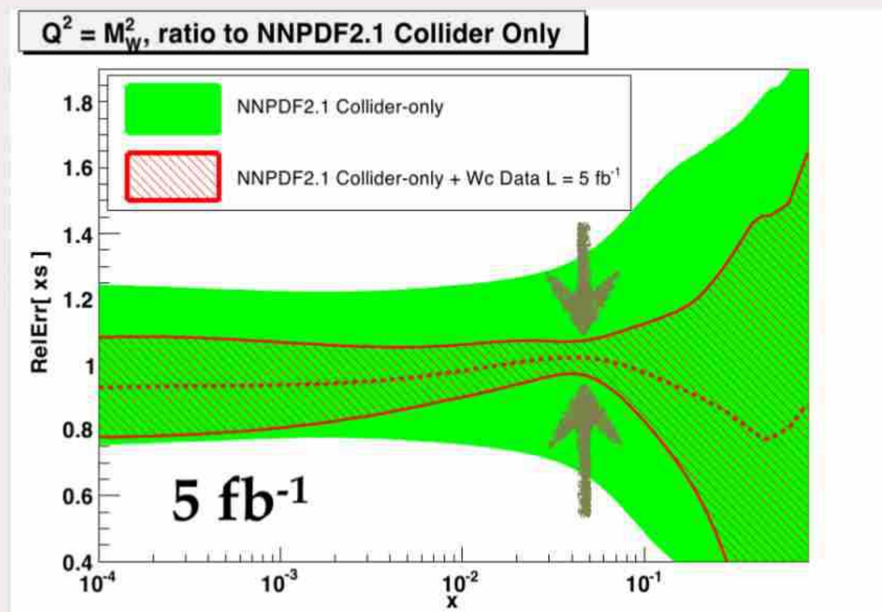
- Signature: a W($\rightarrow l\nu$) and a charm quark with opposite-sign charges
- Variables of interest: $\sigma(W+c)$, $\frac{\sigma(W^{+}+\bar{c})}{\sigma(W^{-}+c)}$, $\frac{d\sigma(W+c)}{d\eta^{l}}$.

Sensitivity of PDF to σ(W+c)



Courtesy of Juan Rojo (CERN)

Predicted impact on PDF uncertainties



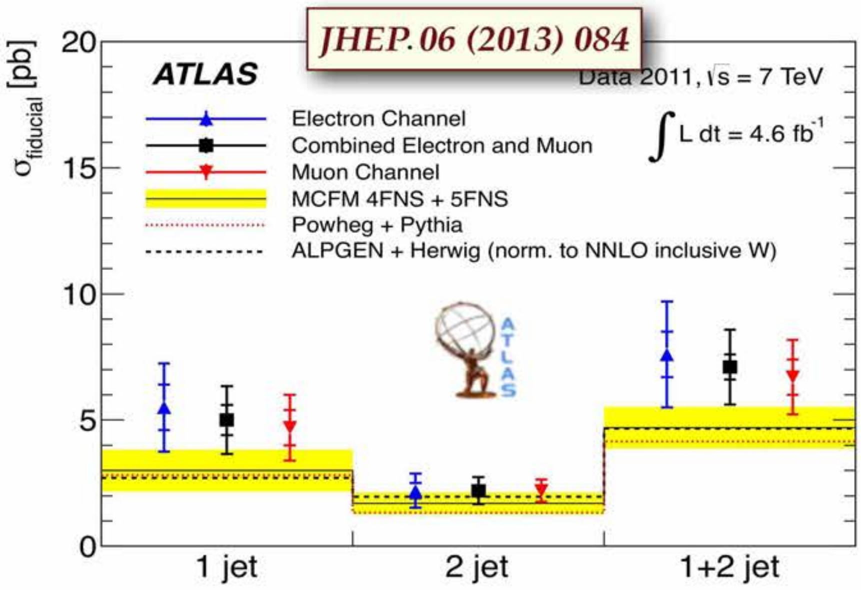
Courtesy of Juan Rojo (CERN)

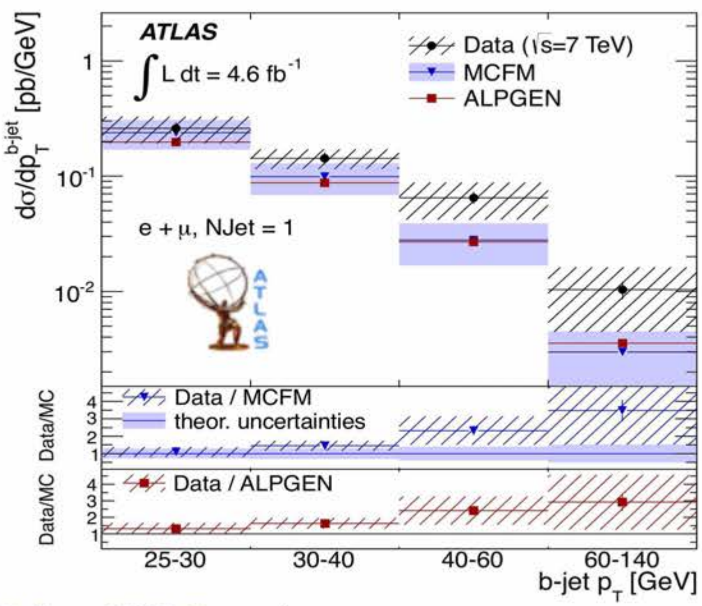
https://indico.cern.ch/getFile.py/access?contribId=10&resId=0&materialId=sli

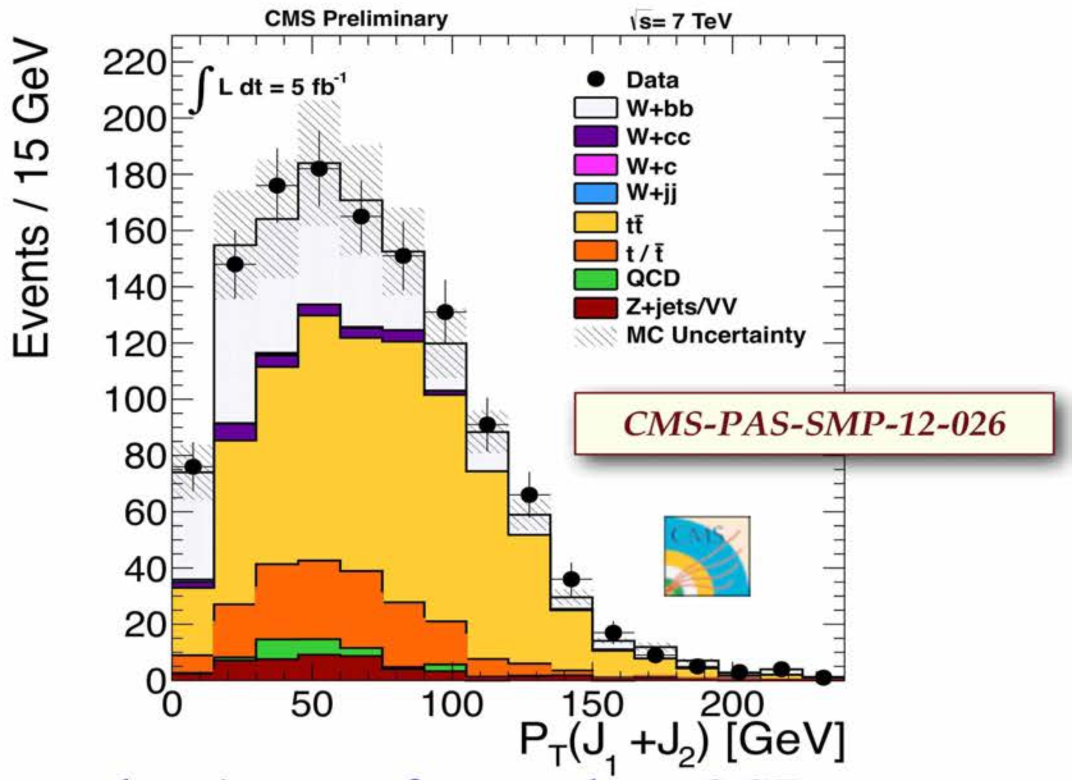
Magnan

Wb investigates heavy quarks in new kinematic regime

W+b(b)







- W+b(b) production confronts the pQCD predictions in the presence of heavy quarks
- fiducial cross section of W+b(b) consistent with MCFM prediction within 1.5σ
- differential cross section shows some tension for increasing b-jet p_T
  - but compatible within unc

Kousouris

TOP QUARK

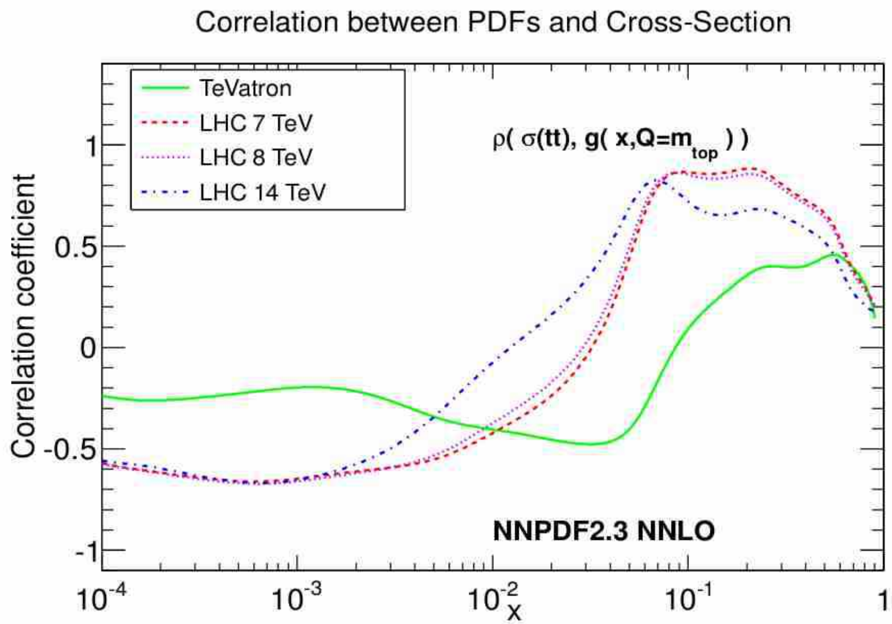
Complete NNLO Results now available; can impact g(x)

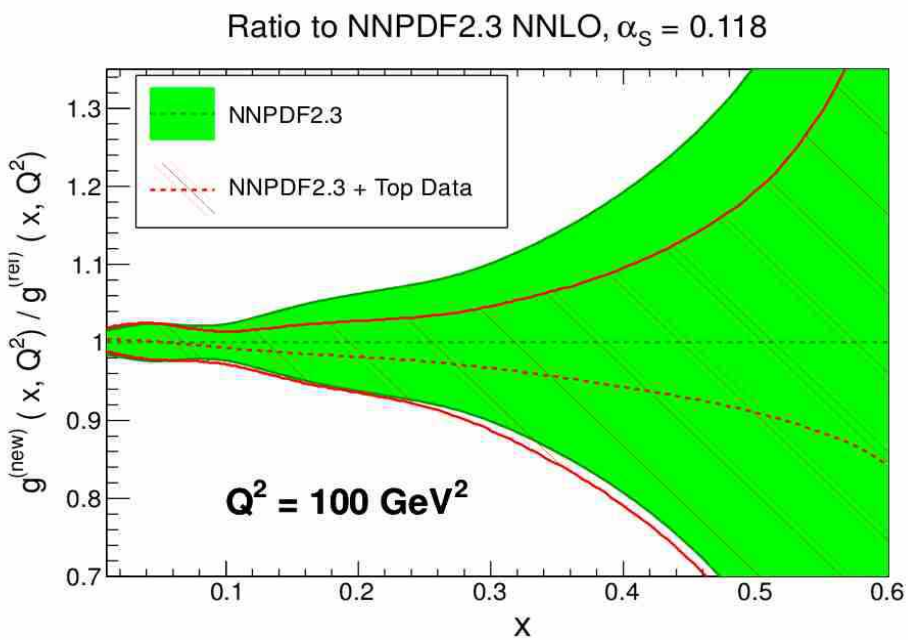
NNLO $t\bar{t}$ pair production: constraining gluon PDF

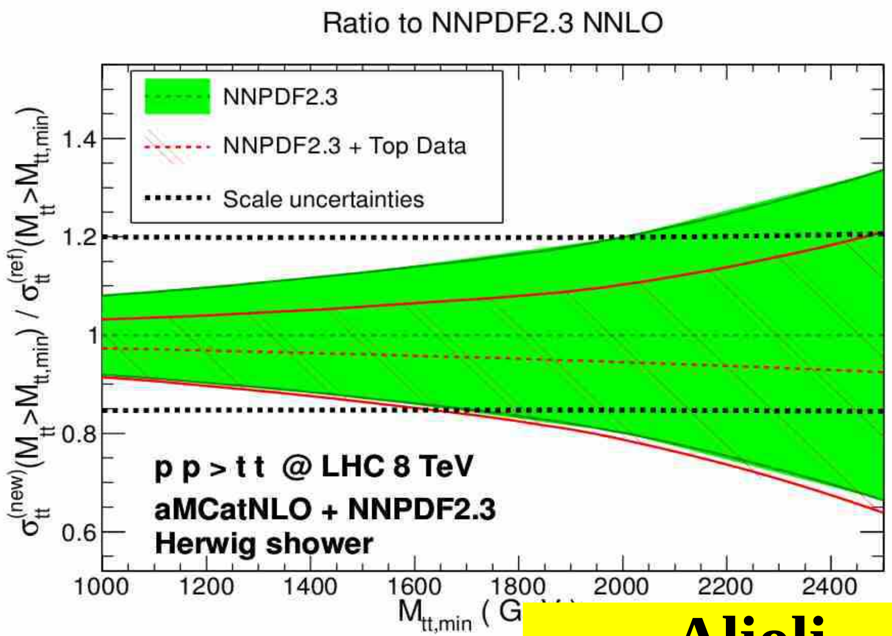
- Top pair x-sec. at LHC highly correlated to gluon PDF in $0.1 \lesssim x \lesssim 0.5$ range
- Including 5 Tevatron and LHC results for $t\bar{t}$ x-sec. into PDF fits

Czakon, Mangano, Mitov, Rojo '13

- Reduces uncertainty on gluon PDF
- Reduces total PDF uncertainty on predictions for gg driven processes







Alioli

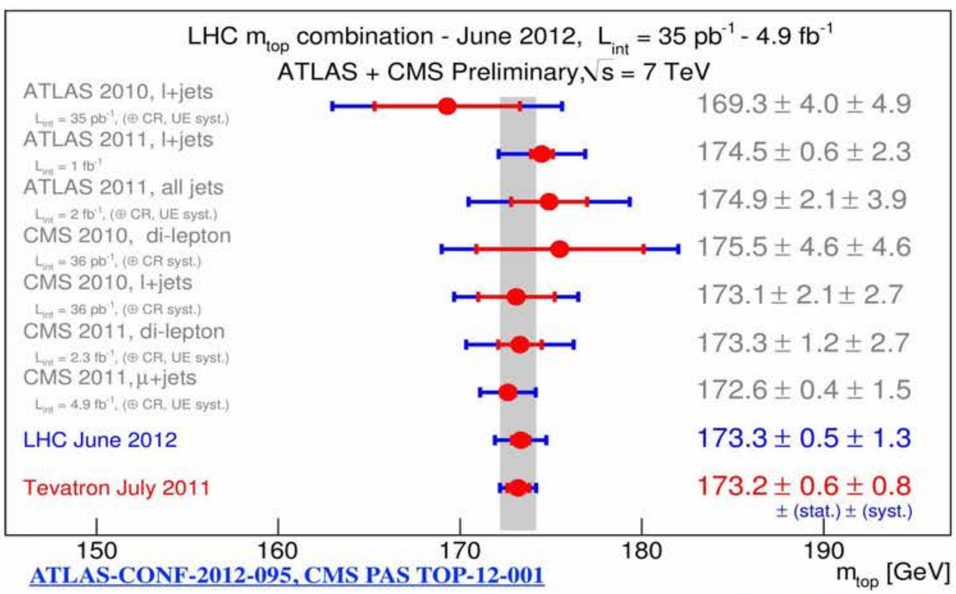
LHC combination

- LHC combination:
  - 7 measurements (ATLAS and CMS), 2010/2011 @7 TeV, up to 4.9 fb^{-1}
  - Combination with the BLUE method
    - does not include latest ATLAS & CMS measurements ➡ work ongoing for TOP2013 !

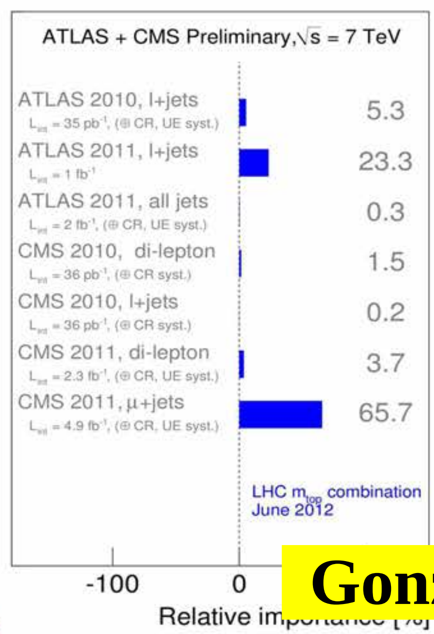
$$m_{\rm top} = 173.3 \pm 0.5\ ({\rm stat}) \pm 1.3\ ({\rm syst})\ \ {\rm GeV}$$

LHC, June 12

- Total uncertainty dominated by systematics (JES, signal modeling, underlying event tune)
  - work ongoing within the TopLHC Working Group to harmonize the tratments of sytematic uncertainties



ATLAS-CONF-2012-095, CMS PAS TOP-12-001

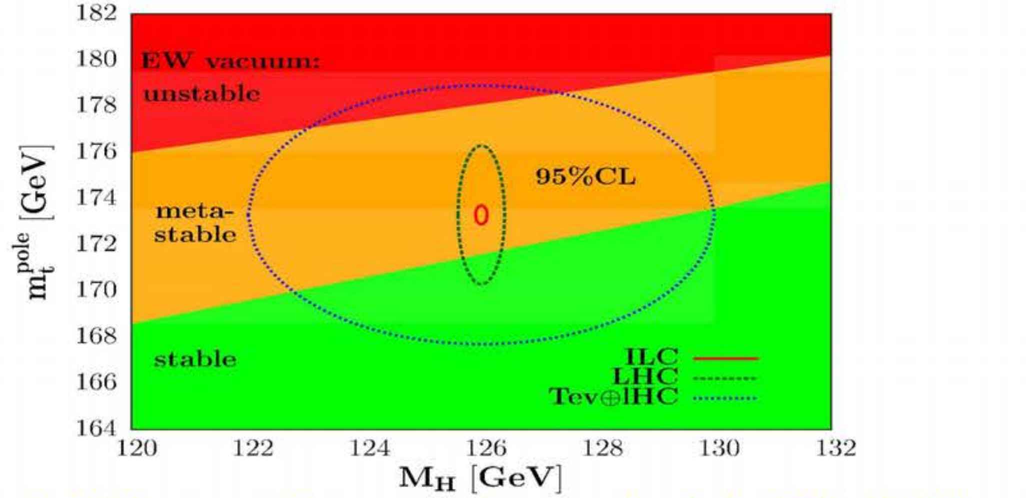


Gonzalez-Sevilla

Top mass impacts vacuum stability condition

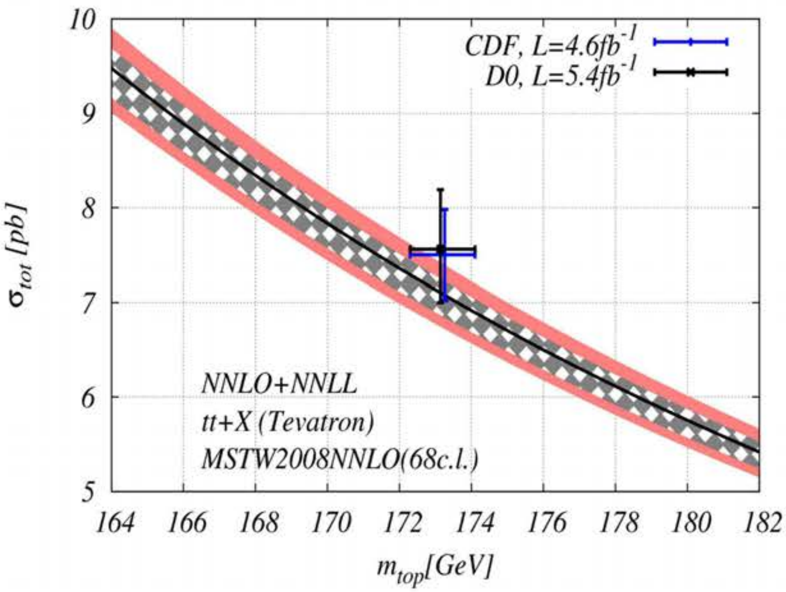
t-quark mass

- m_t(MC)=173.3±1 GeV (Tevatron/LHC)
- m_t(pole)≈ m_t(MC) - 1 GeV
- $m_t(m_t)$≈ m_t(pole) - 9 GeV



Vacuum stability condition requires m_t(pole)~171 GeV

sa, Djouadi, Moch PLB 716, 214 (2012)



CDF&D0	ABM11	JR09	MSTW08	NN21
$m_t^{\overline{MS}}(m_t)$	$162.0^{+2.3\,+0.7}_{-2.3\,-0.6}$	$163.5^{+2.2\,+0.6}_{-2.2\,-0.2}$	$163.2^{+2.2\,+0.7}_{-2.2\,-0.8}$	$164.4^{+2.2\,+0.8}_{-2.2\,-0.2}$
m_t^{pole}	$171.7^{+2.4\,+0.7}_{-2.4\,-0.6}$	$173.3^{+2.3\,+0.7}_{-2.3\,-0.2}$	$173.4^{+2.3\,+0.8}_{-2.3\,-0.8}$	$174.9^{+2.3\,+0.8}_{-2.3\,-0.3}$
(m_t^{pole})	$(169.9^{+2.4\,+1.2}_{-2.4\,-1.6})$	$(171.4^{+2.3\,+1.2}_{-2.3\,-1.1})$	$(171.3^{+2.3\,+1.4}_{-2.3\,-1.8})$	$(172.7^{+2.3\,+1.4}_{-2.3\,-1.2})$

Bärnreuther, Czakon, Mitov hep-ph/1204.5201

From the Tevatron c.s. m_t(pole)~171 GeV

ATLAS&CMS	ABM11	JR09	MSTW08	NN21
$m_t^{\overline{MS}}(m_t)$	$159.0^{+2.1\,+0.7}_{-2.0\,-1.4}$	$165.3^{+2.3\,+0.6}_{-2.2\,-1.2}$	$166.0^{+2.3\,+0.7}_{-2.2\,-1.5}$	$166.7^{+2.3\,+0.8}_{-2.2\,-1.3}$
m_t^{pole}	$168.6^{+2.3\,+0.7}_{-2.2\,-1.5}$	$175.1^{+2.4\,+0.6}_{-2.3\,-1.3}$	$176.4^{+2.4\,+0.8}_{-2.3\,-1.6}$	$177.4^{+2.4\,+0.8}_{-2.3\,-1.4}$
(m_t^{pole})	$(166.1^{+2.2\,+1.7}_{-2.1\,-2.3})$	$(172.6^{+2.4\,+1.6}_{-2.3\,-2.1})$	$(173.5^{+2.4\,+1.8}_{-2.3\,-2.5})$	$(174.5^{+2.4\,+2.0}_{-2.3\,-2.3})$

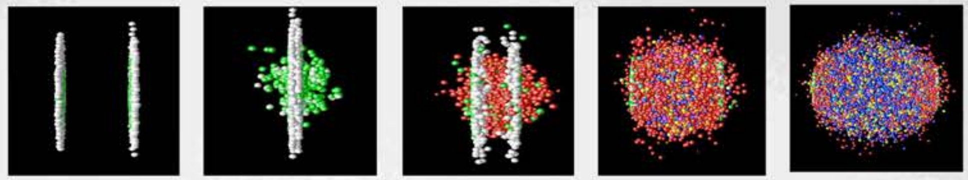
Alekhin

Stronger correlation between m_t, PDFs and α_s at LHC

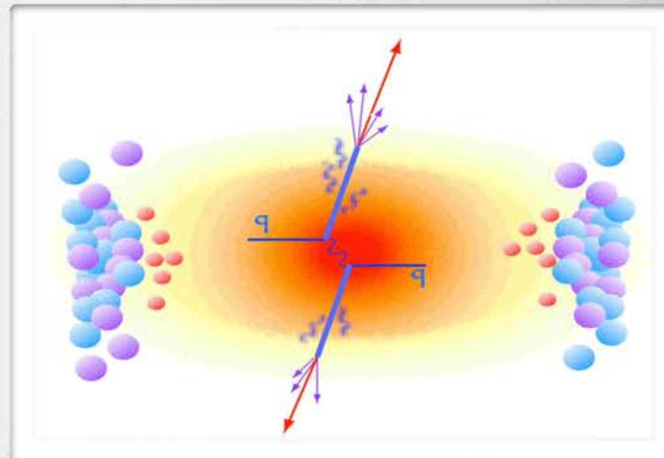
NUCLEAR DIMENSION

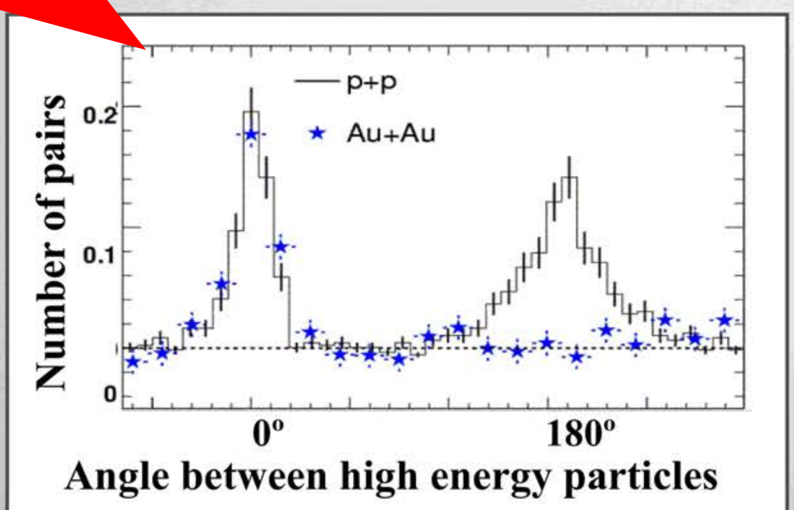
Nuclear Beams to play with

Will Brooks (ATLAS)
18 December 2009
VIII Latin American Symposium on
Nuclear Physics and Applications



- The Relativistic Heavy Ion Collider (RHIC/BNL) has discovered a *new state of matter* in heavy ion collisions
- Experimental evidence indicates it is a hot, dense, strongly interacting system that behaves as a liquid with ultra-low viscosity
- The most compelling evidence that a super-dense medium is formed is ***jet quenching*** - *the disappearance of one of the jets in high-p_T two-jet events:*





- The phenomenon is qualitatively understood, but a number of puzzles remain
- The study of jet quenching in heavy ion collisions at LHC offers many new possibilities:
  - Much wider kinematic range and larger cross sections
  - Well-defined jets
  - Heavy quark jets

Friday, December 18, 2009

Heavy ions: centrality dependence of jet suppression

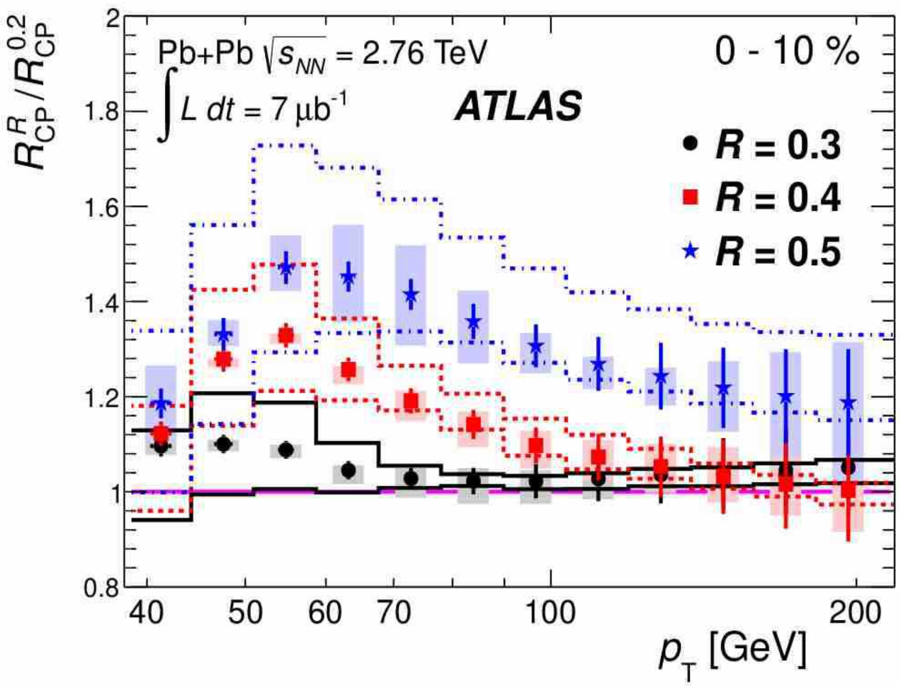
- Jet radius and p_T dependence of inclusive jet suppression in PbPb collisions at $\sqrt{s_{NN}} = 2.76$ TeV (PLB 719 (2013) 220)
- The centrality dependence of the jet yield is characterized by the jet "central-to-peripheral ratio", R_{CP} (using 60-80% as the peripheral reference centrality interval)

$$R_{CP}^{meas}(p_T)|_{cent} = \frac{1}{R_{coll}^{cent}} \left(\frac{\frac{N_{jet}^{cent}(p_T)}{N_{evt}^{cent}}}{\frac{N_{jet}^{60-80}(p_T)}{N_{evt}^{60-80}}} \right)$$

where $R_{coll} \equiv \langle N_{coll} \rangle / \langle N_{coll}^{60-80} \rangle$

R_{CP} ratios for different jet radii:

- Error bars: statistical uncertainties
- Shaded boxes: partially correlated systematic errors
- Lines: fully correlated systematic errors



The inclusive jet yield is observed to be suppressed by a factor of about two in central collisions relative to peripheral collisions

A. Ruiz (ISU) QCD@LHC 2013 3

Ruiz

Physics Scorecard: Circa ~2013

THEORY:

- NLO Calculations routine and automated
  - Many NNLO completed
- Major advances in NLO + Monte Carlo merging
- Many Resummation calculations
- Top quark: discovered & computed to NNLO
- W/Z: fundamental tool: standard candle
- s(x) PDF: uncertain, but improving fro LHC data

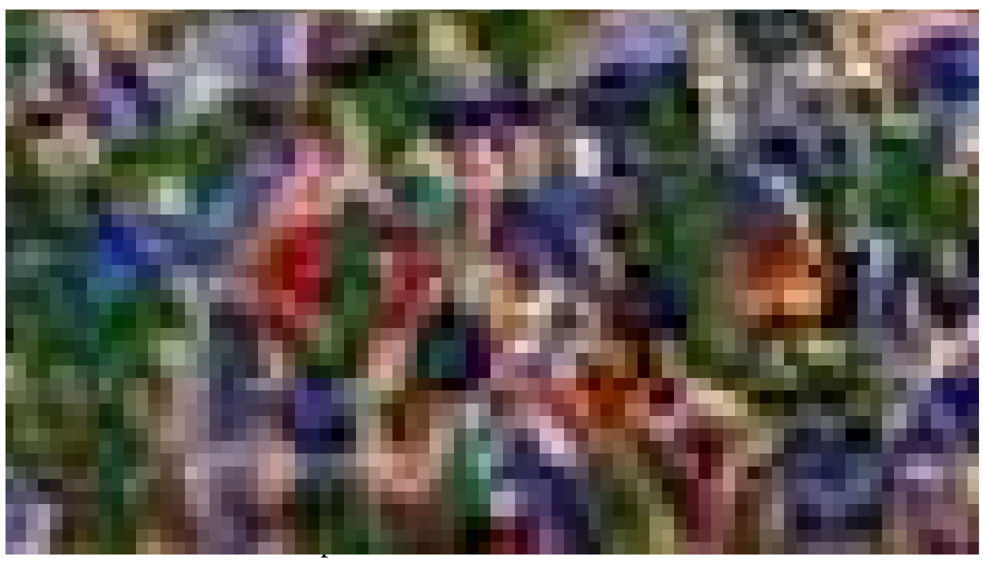
EXPERIMENT:

Closing the HERA era, and beginning the LHC age

MY BET:

There will be more clever people with more good ideas,
The data will make us even smarter


QCD@LHC2013
2-6 September 2013
DESY, Hamburg



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Working groups and Convenors

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Group 2: Hard QCD and MC
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Matteo Cacciari (theory, jets)

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Group 3: Multi-parton dynamics
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