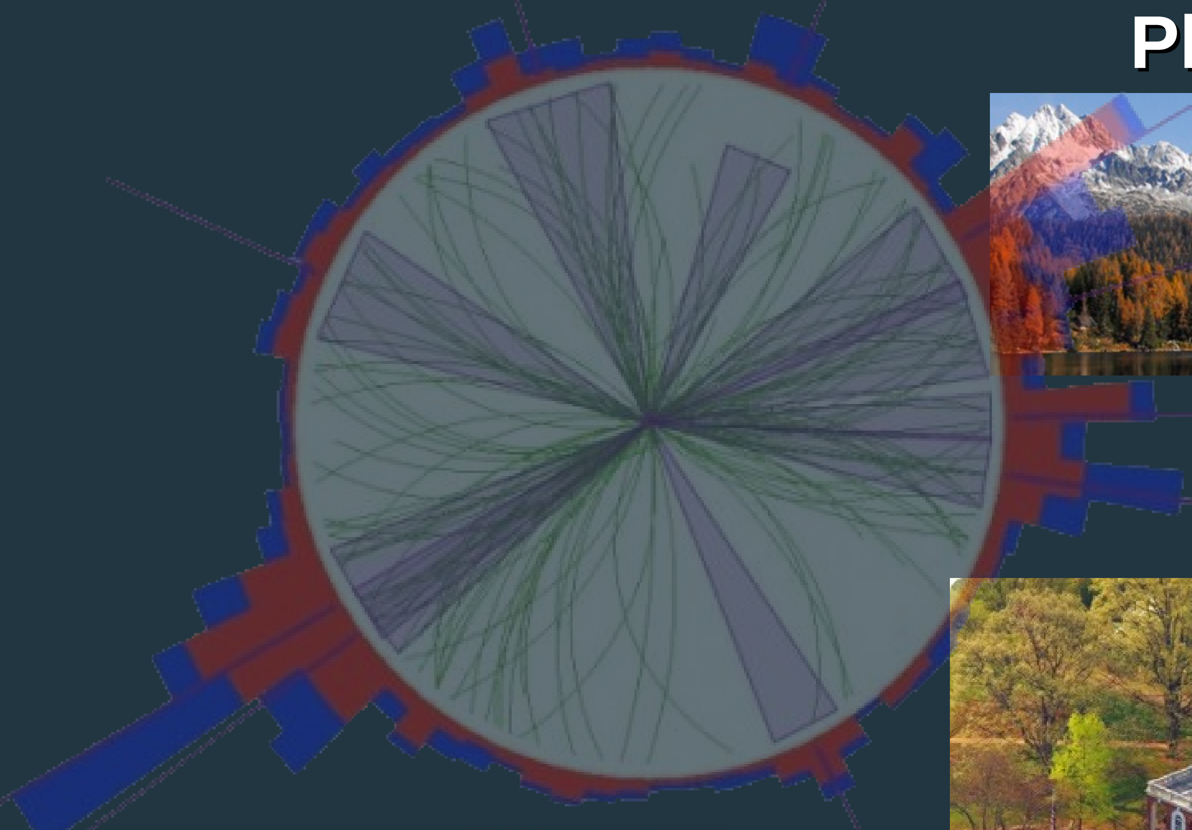
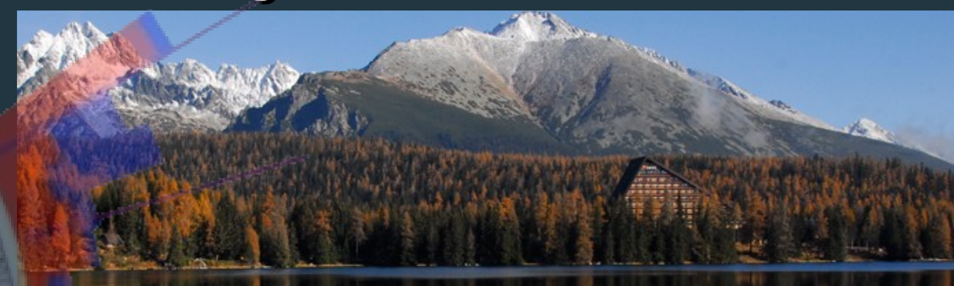
A survey of

Jet Production Studies at Colliders



Physics in Collision



Bob Hirosky, UNIVERSITY of VIRGINIA

A survey of

Jet Production Studies at Colliders

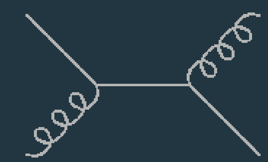
Physics in Collision

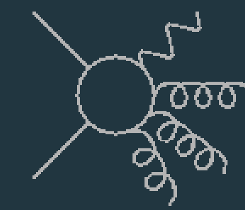
+ general perspectives on the trade

Bob Hirosky, UNIVERSITY *of* VIRGINIA

Jet production

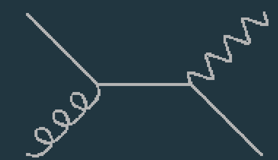
Consider events with final state partons



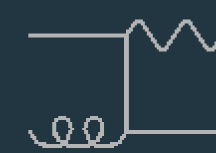


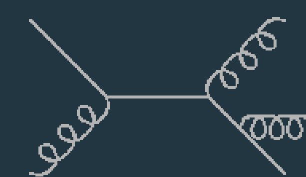
Generally: $A + B => parton + X$

Wide range of phenomena including:



- Hard scattering of partons
- Decay of heavy, short-lived particles (e.g. weak bosons)
- May involve mixed strong, weak, EM vertices





Jet production

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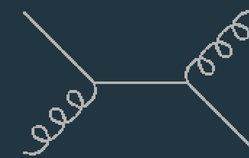

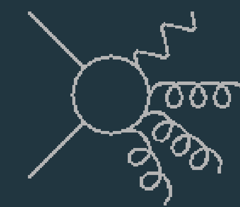

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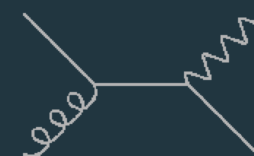

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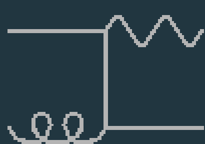
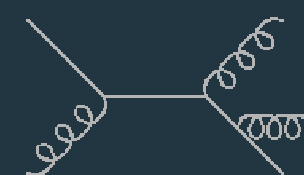
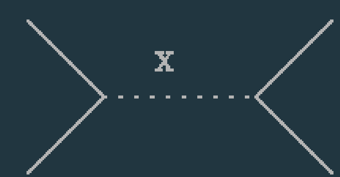


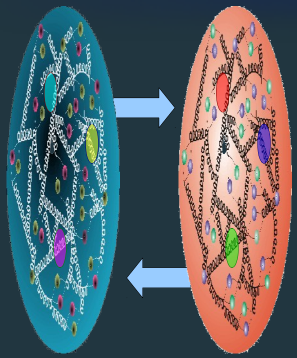


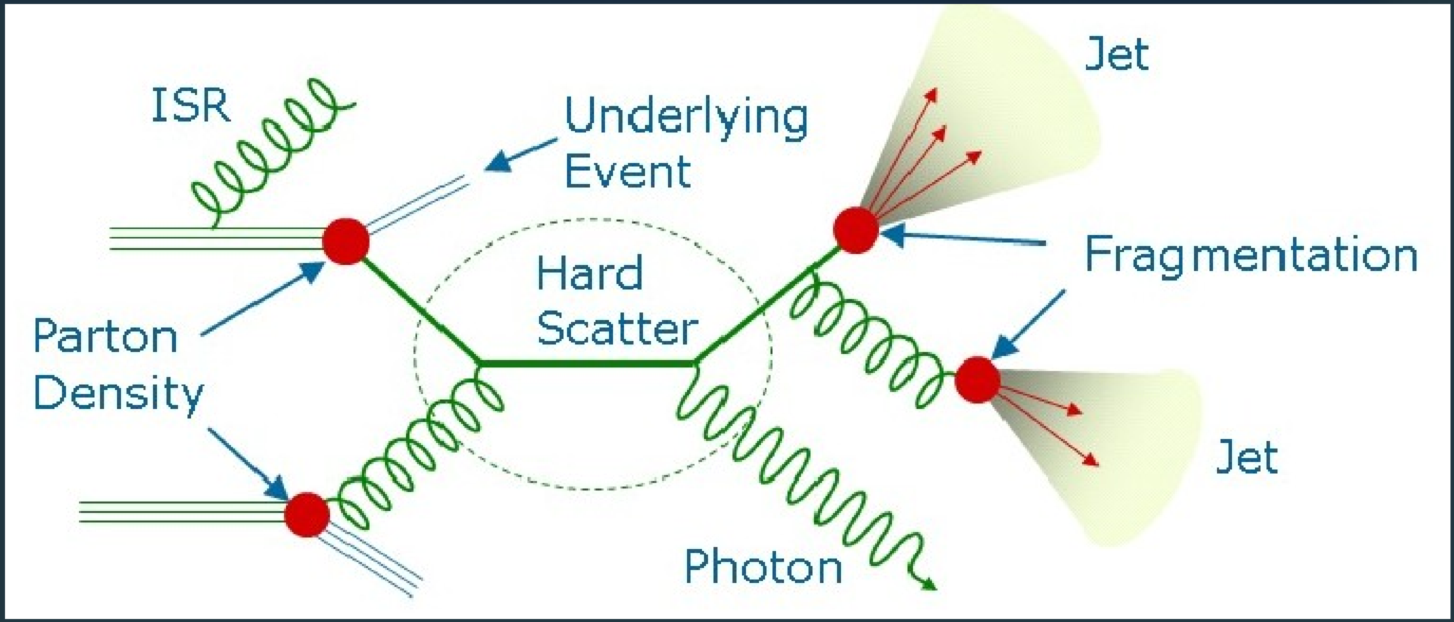
Use to study:



- Strong dynamics, couplings, PQCD, NP models
- Hadron structure and new scales of structure
- Measure hadronic decay modes, seek new massive states

Starting picture

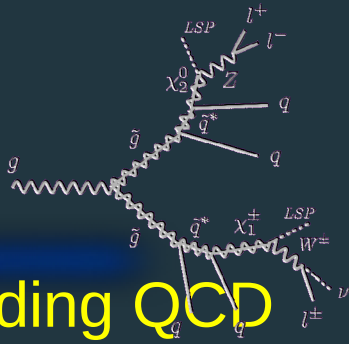




Problem "neatly" factorizes into:

- Perturbative hard scatter (+ hard radiation) [short time/distance]
- Non-perturbative parton density and fragmentation models (+soft radiation) [long time/distance]

More motivations



- searches for new phenomena limited w/o proper understanding QCD background

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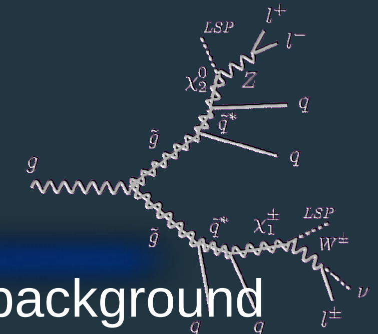

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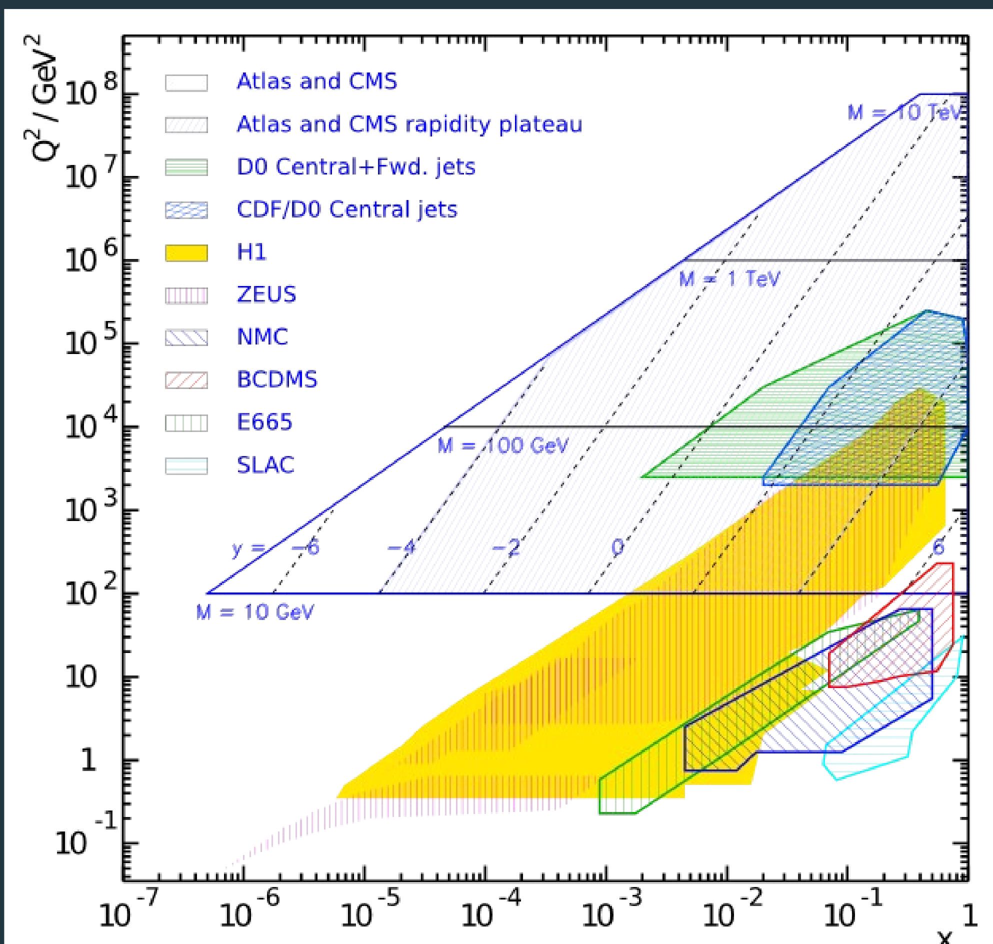
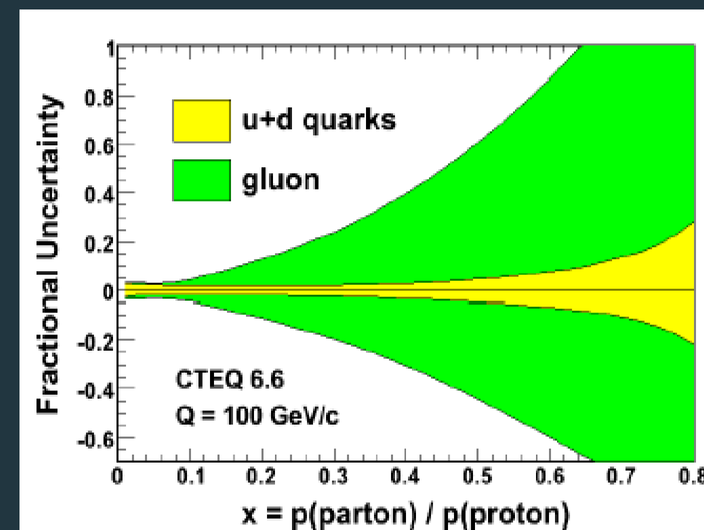
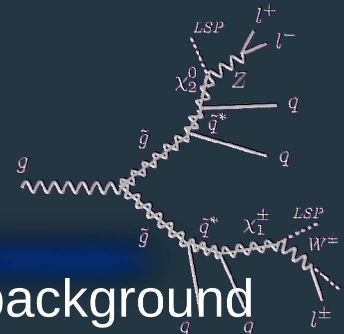
- providing unique constraints on PDFs: (also see talk by J. Bluemlein)

accessible x-Q^2 regions complementary at fixed target, DIS, Tevatron and LHC







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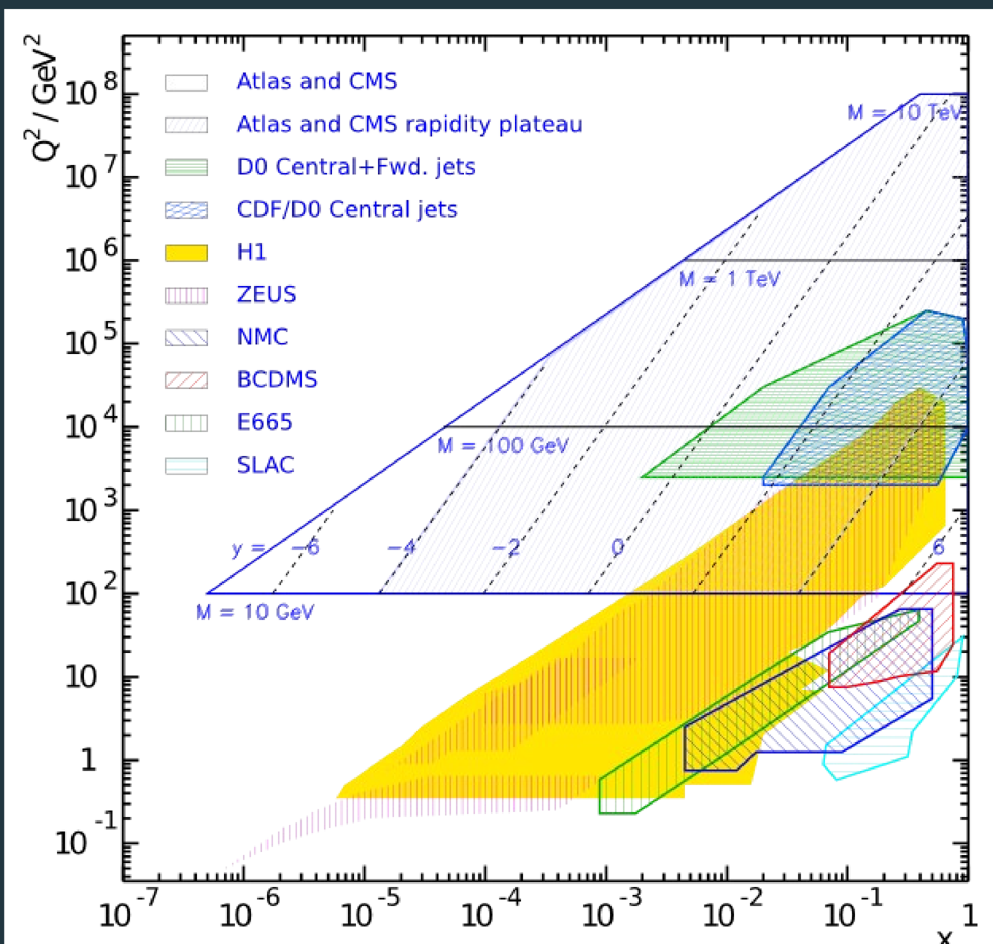

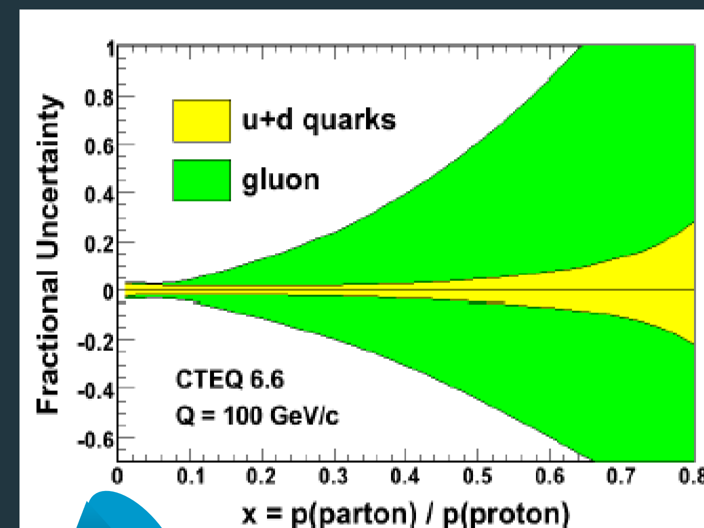

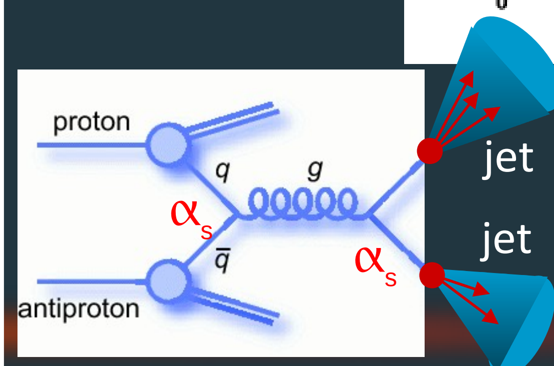

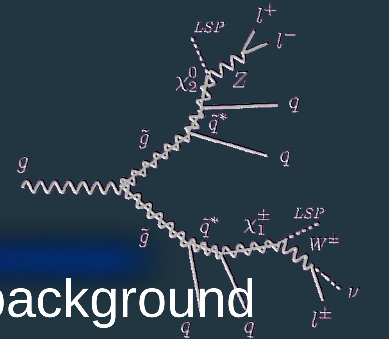

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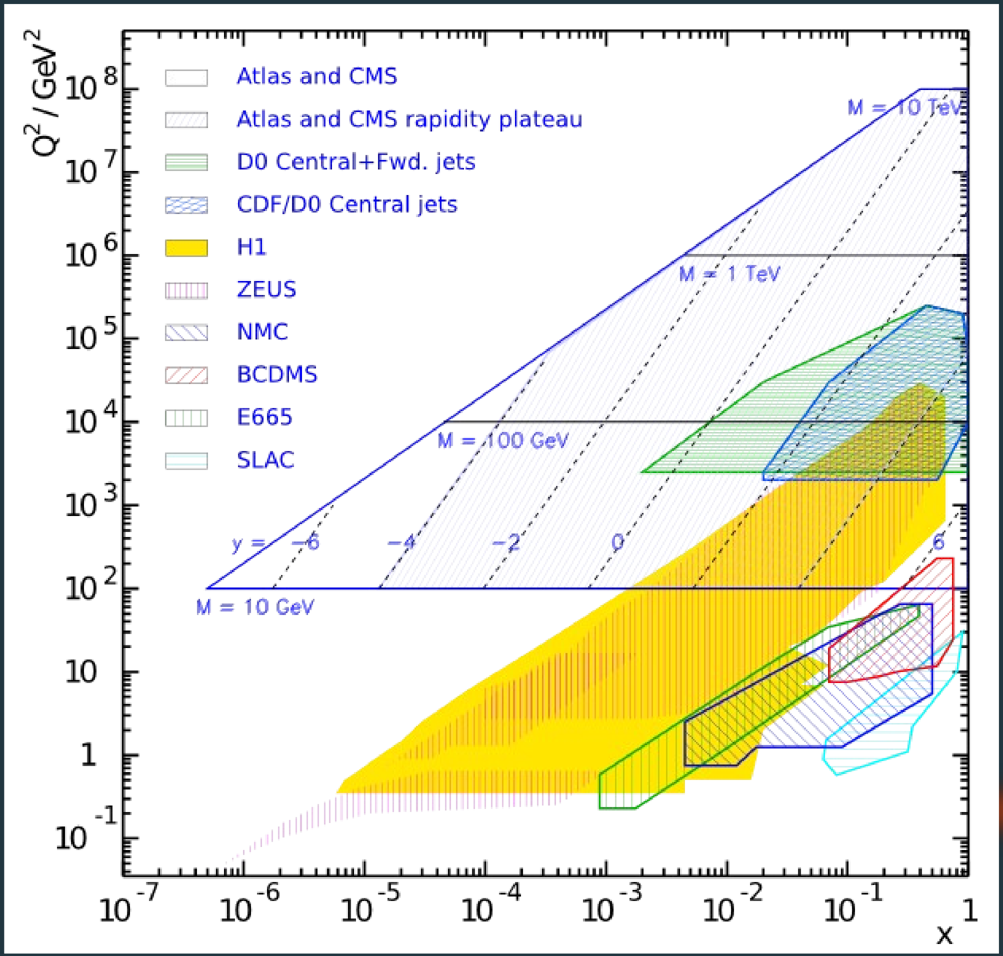
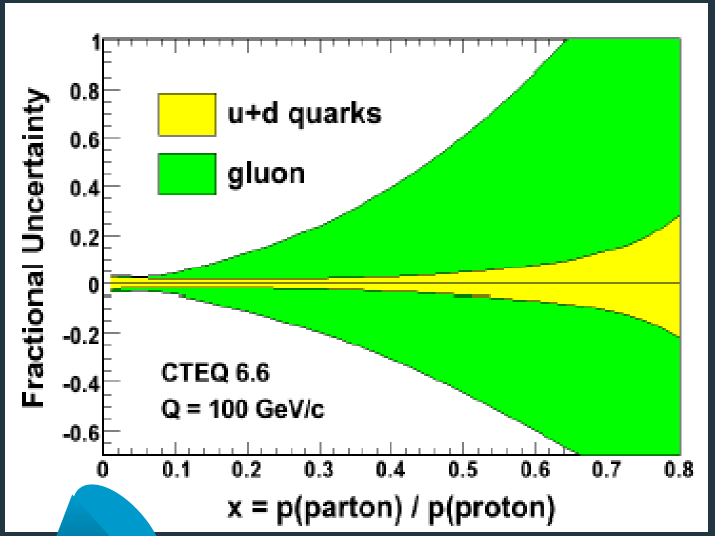
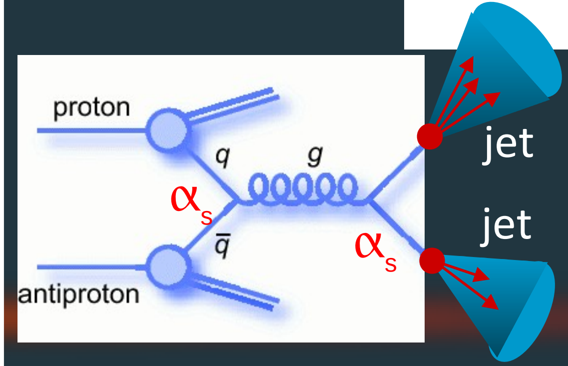
- studying internal jet substructure (see talk by E. Duchovni)

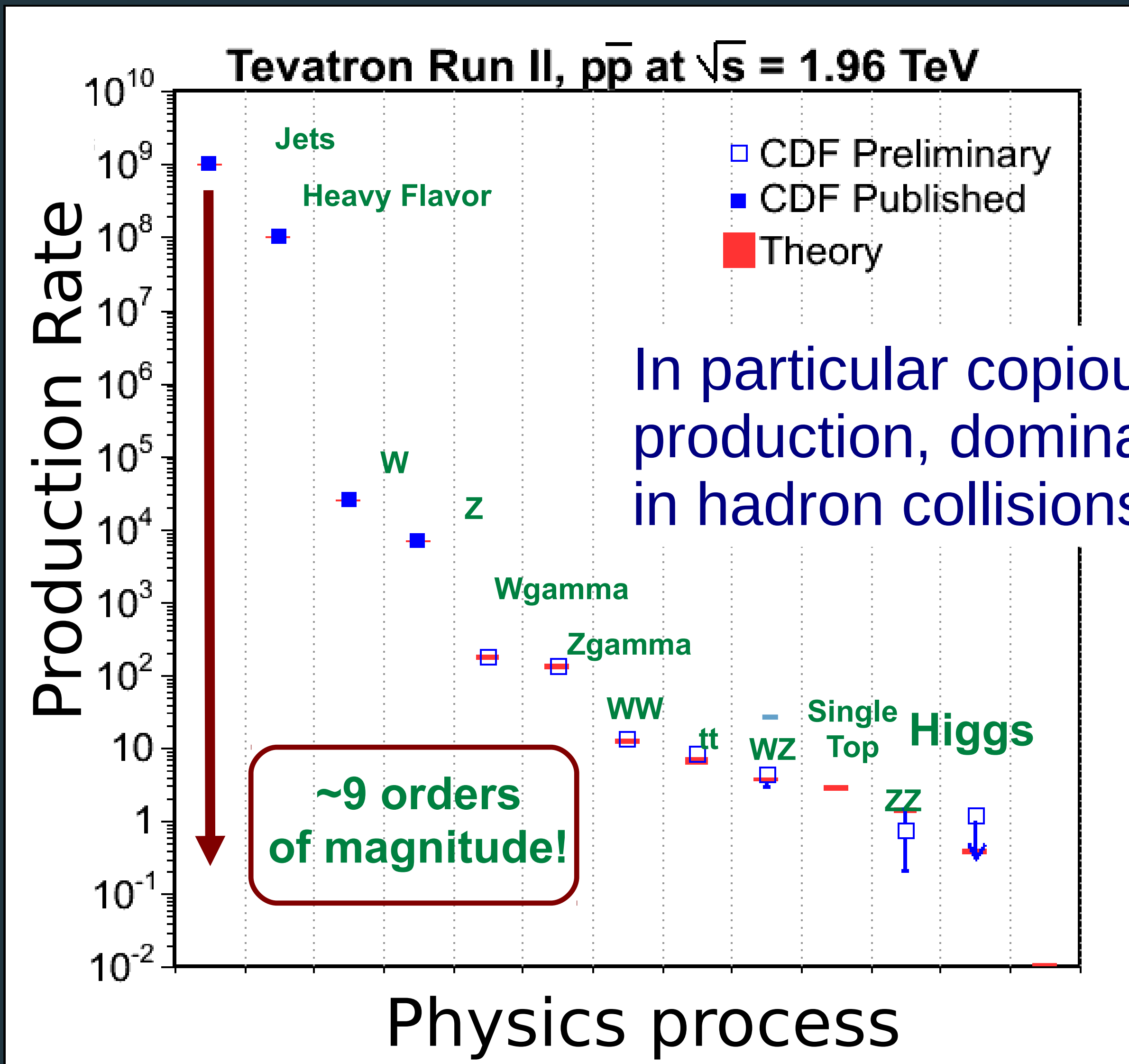






Major challenge of

Standard Model Physics Processes



In particular copious jet production, dominates in hadron collisions

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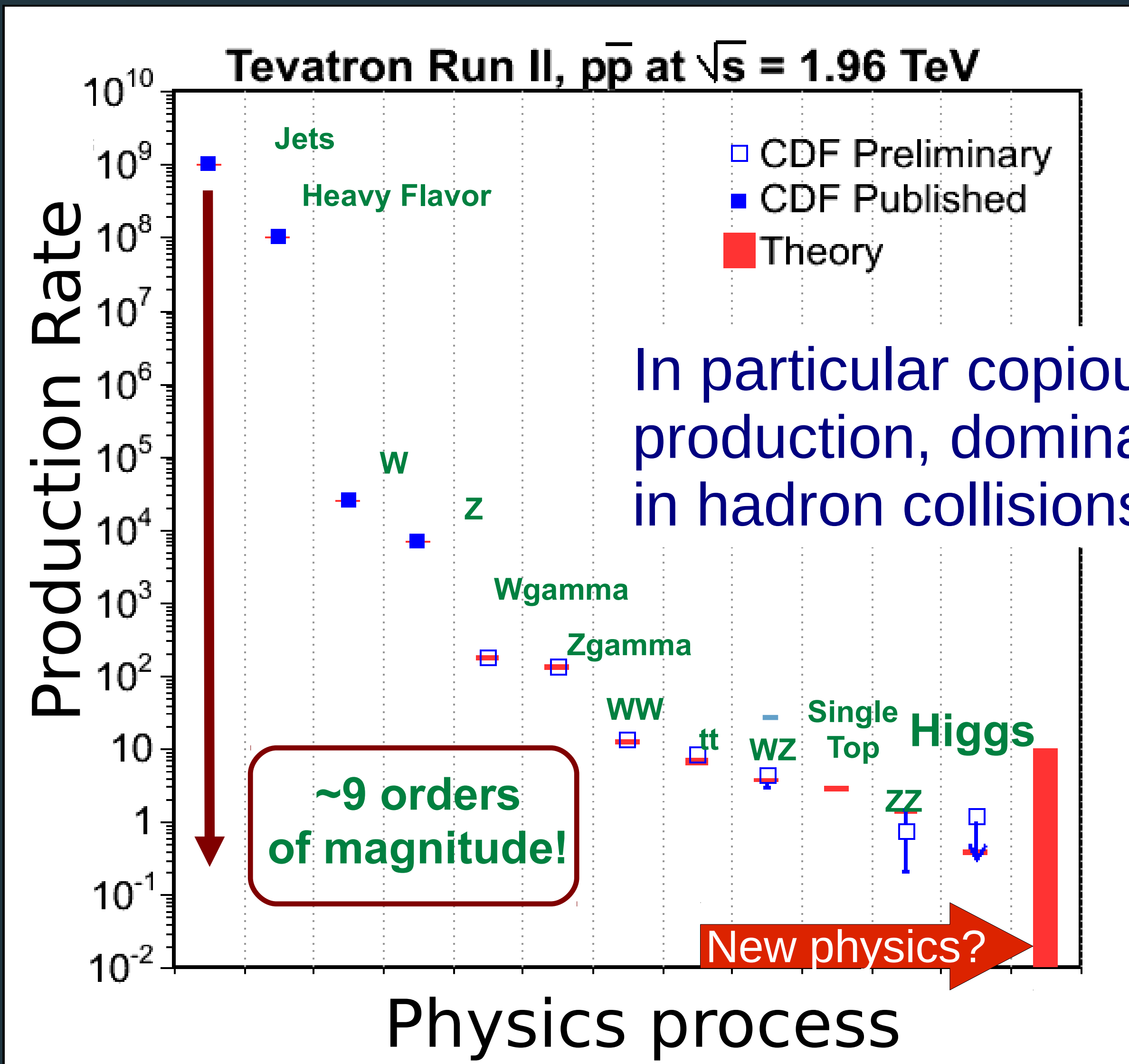
BSM Physics Processes



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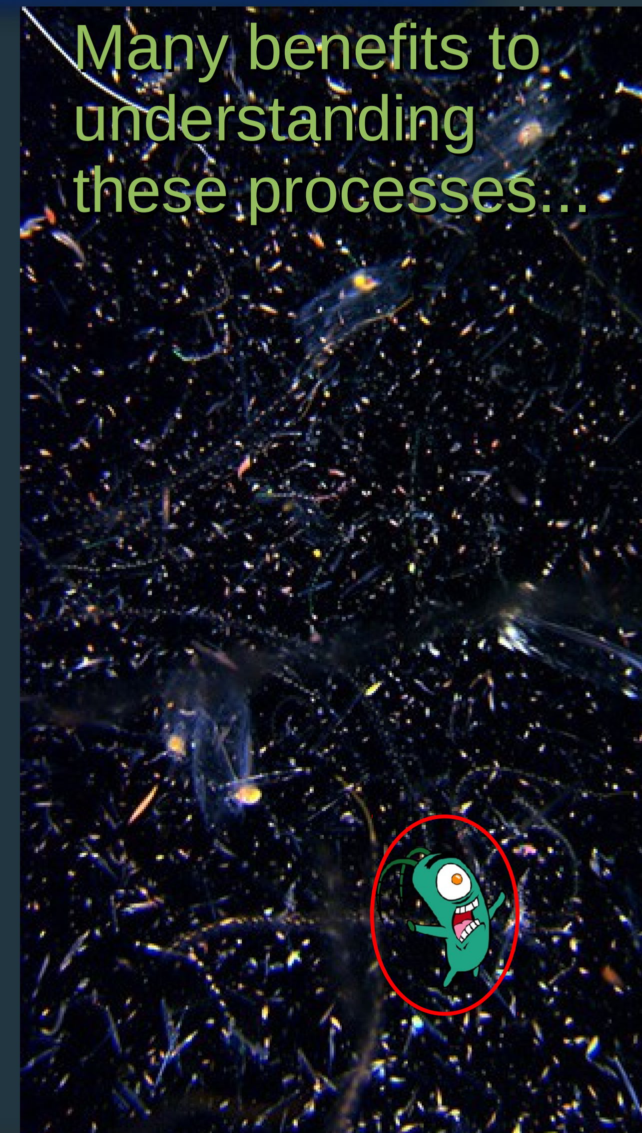

Many benefits to understanding these processes…

I know one when I see one...

But what is a jet?

Important point: A jet is what you define to be a jet.

We're not dealing with elementary objects: (e, gamma, μ, etc).
Jets are defined by algorithms, different algorithms find different jets.

A good jet algorithm:

- Gives consistent results applied to partons, hadronization particles, or to detector-level information (tracks, energy clusters, ...)

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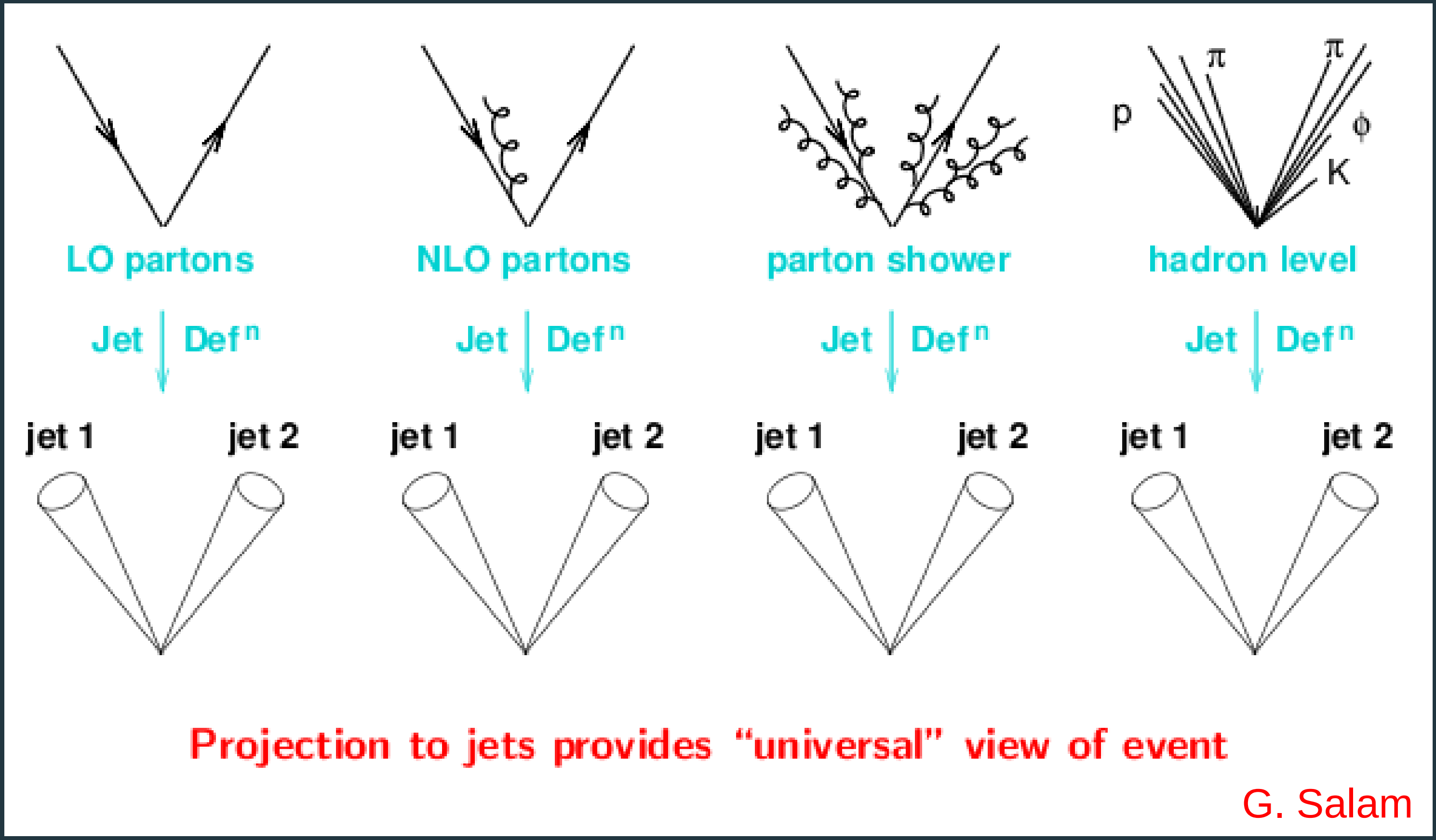
- Is *relatively straightforward* to calibrate (good resolution, smallish corrections, ...)

A good algorithm



Same performance on theoretical objects and also observables...

Typical clustering schemes

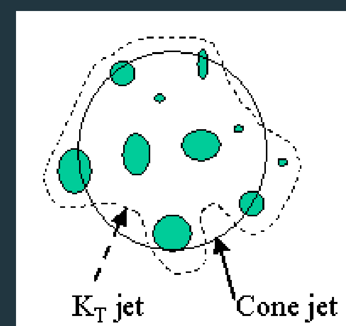
Can roughly think of jet algorithms in classes of

Recombination algorithms

KT – algorithm: ~successively combine close neighbors starting with low relative momentum 4-vectors, up to some stopping criteria ==> “undo showering”

Anti-KT – algorithm: ~successively merge close neighbors starting with high relative p_T 4-vectors. (also finds relatively circular jets)

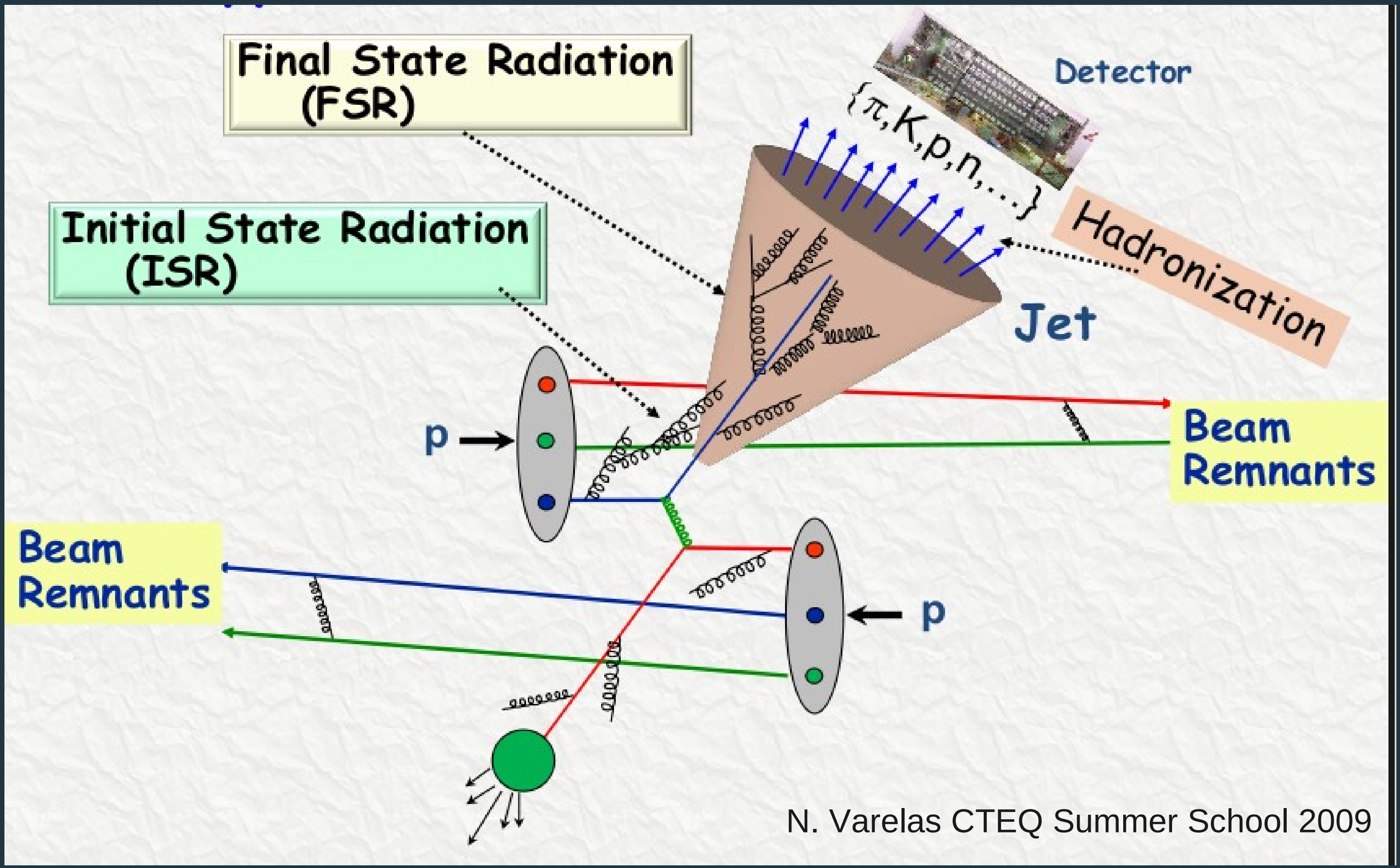
Cone Algorithms



Iterate position of fixed cones until geometric center = PT-weighted center of 4-vectors

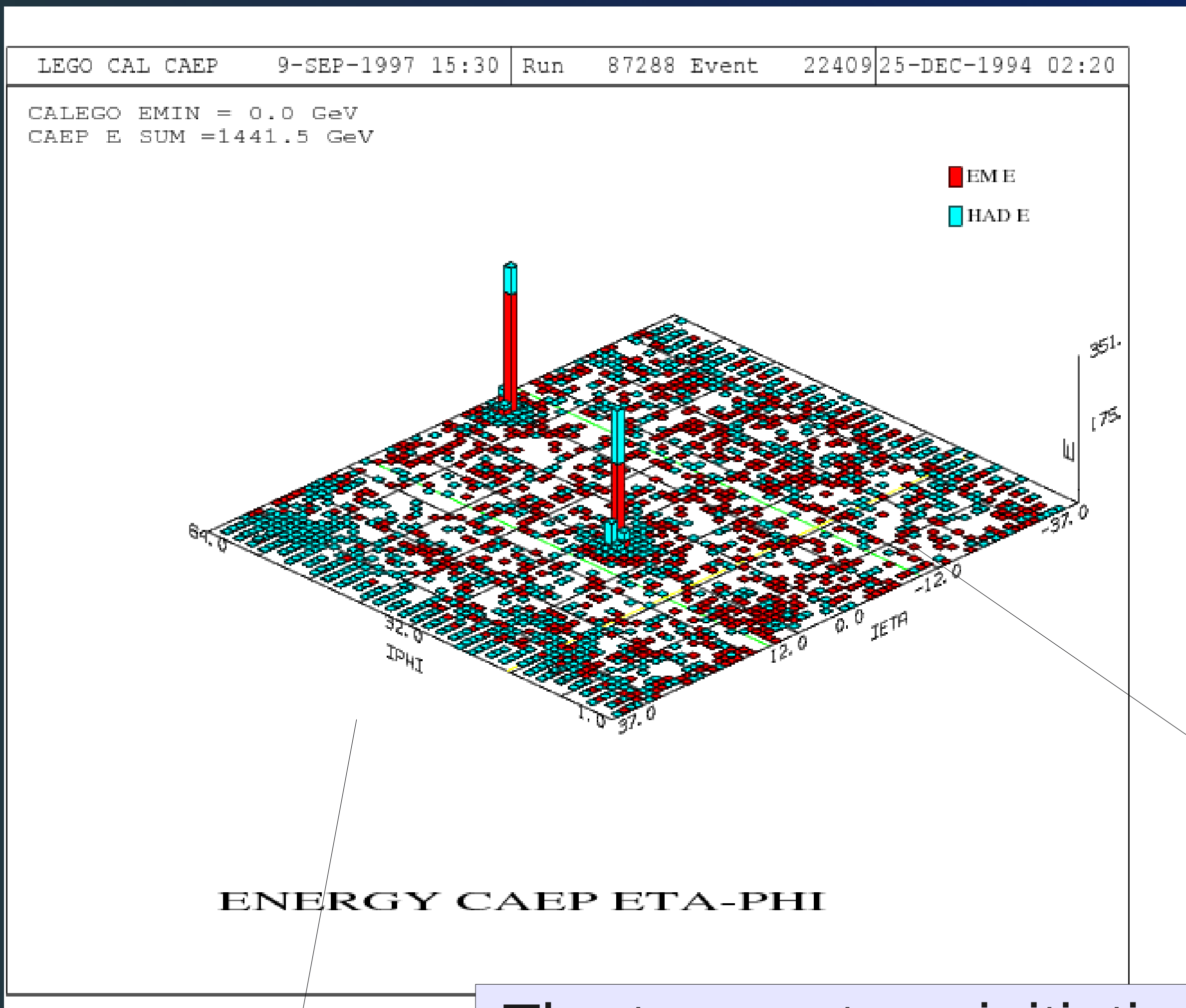
Apply merge/split algorithm for overlapping cones.

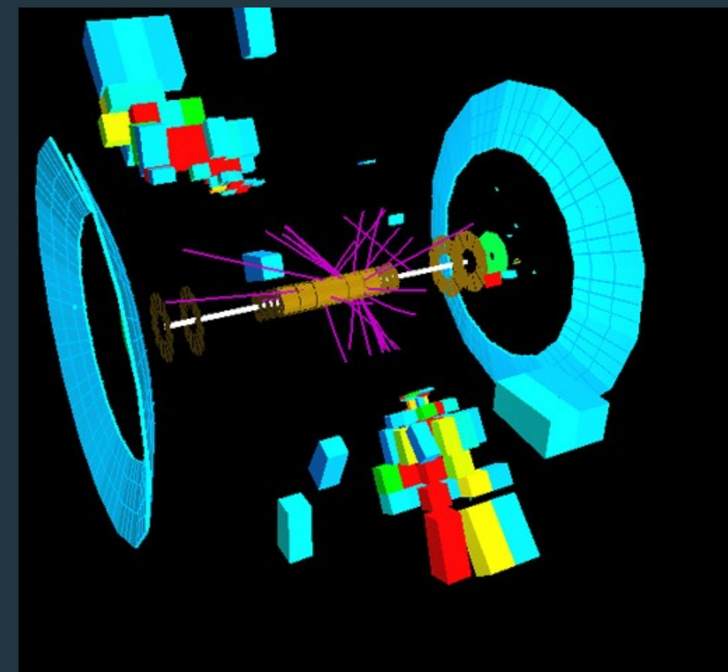
Jet production (redux)



N. Varelas CTEQ Summer School 2009

Jets: the classic hard scatter





“Typical” jet event

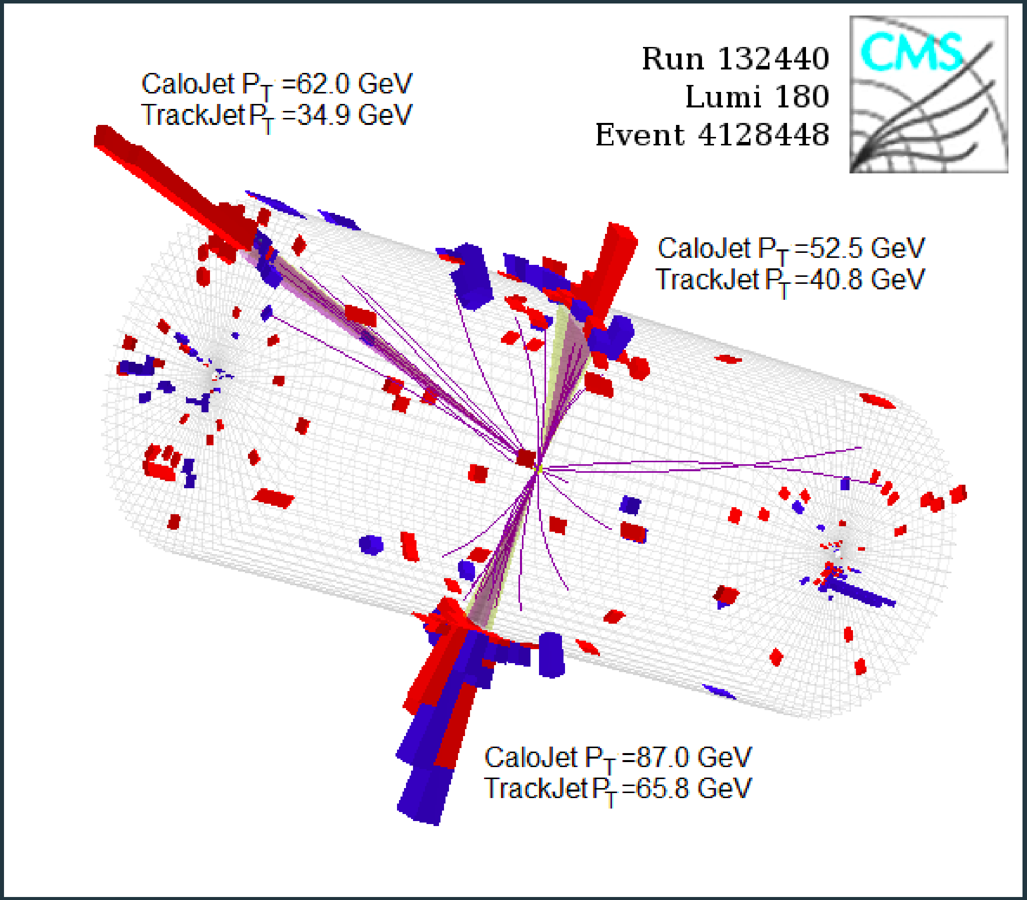
The two partons initiating these jets at DØ, carried about 2/3 of the incoming protons' momentum!

Notice
Low-level
“underlying event”

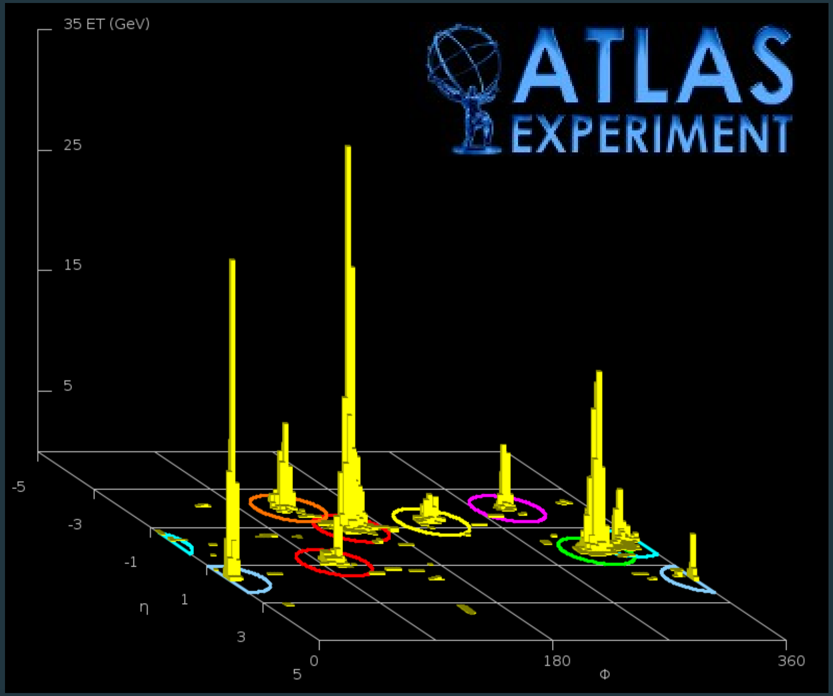
Jets: the classic hard scatter

These are very real objects despite some ambiguity in definitions

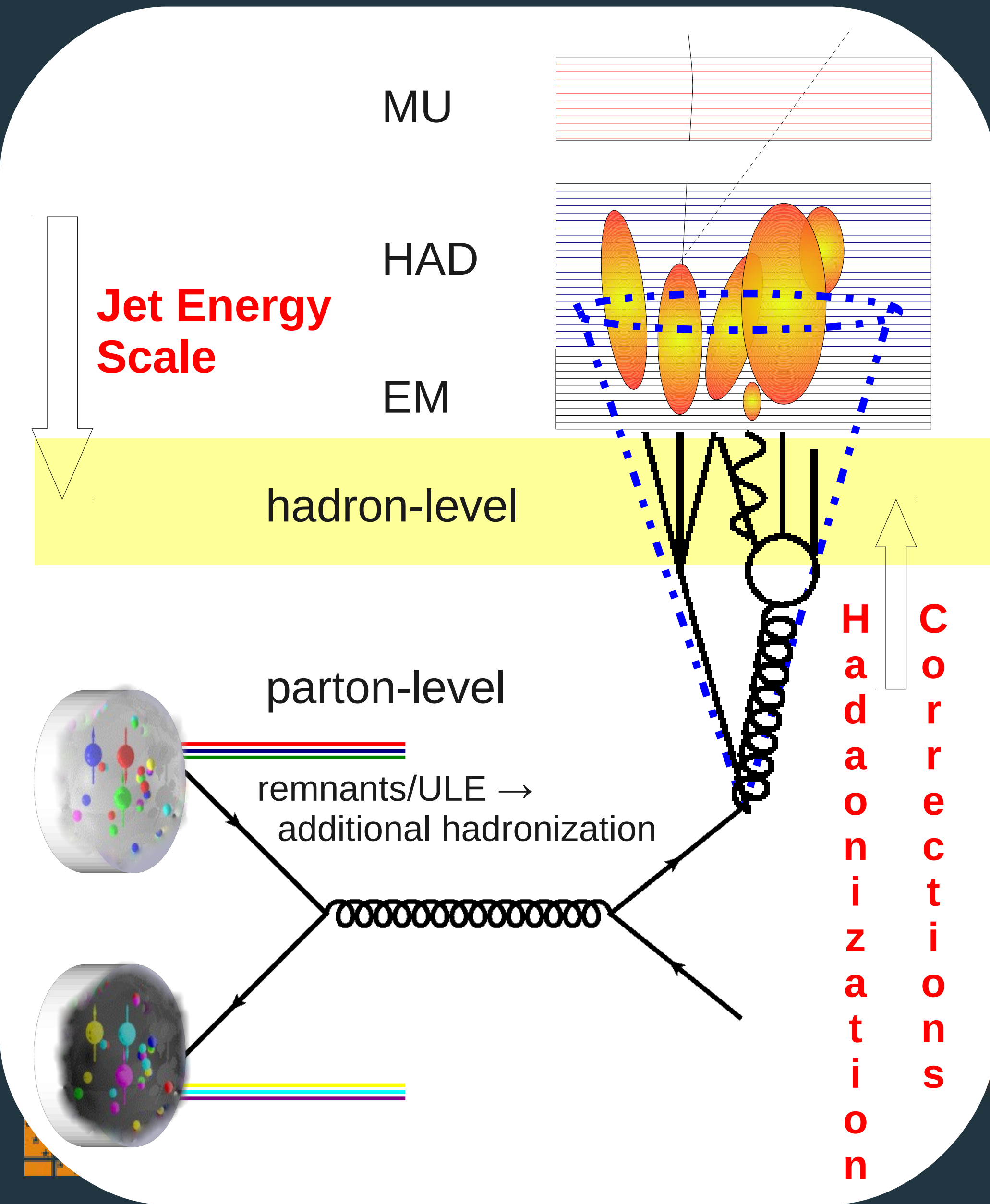
3 jet event



a very busy 8 jet event



Matching data to theory



Clustering algorithm chosen to accurately define jets at detector particle, parton levels

Observed energies corrected to particle(hadron)-level expectations

pQCD calculations are corrected for non-perturbative effects of hadronization and underlying event

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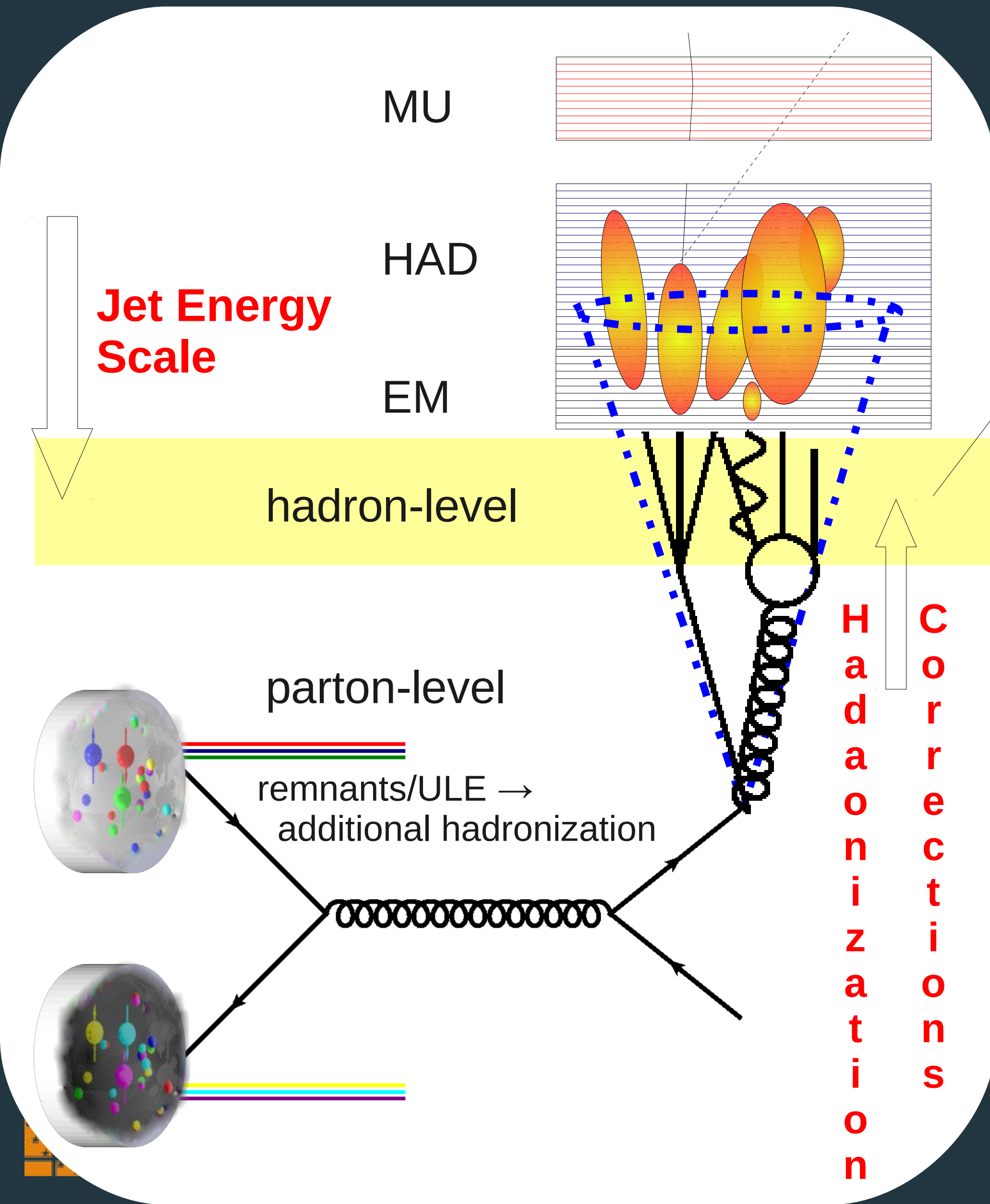


Clustering algorithm chosen to accurately define jets at detector particle, parton levels

(often) Compare data/MC here

Observed energies corrected to particle(hadron)-level expectations

pQCD calculations are corrected for non-perturbative effects of hadronization and underlying event

Theory/experiment typically compared at particle-level

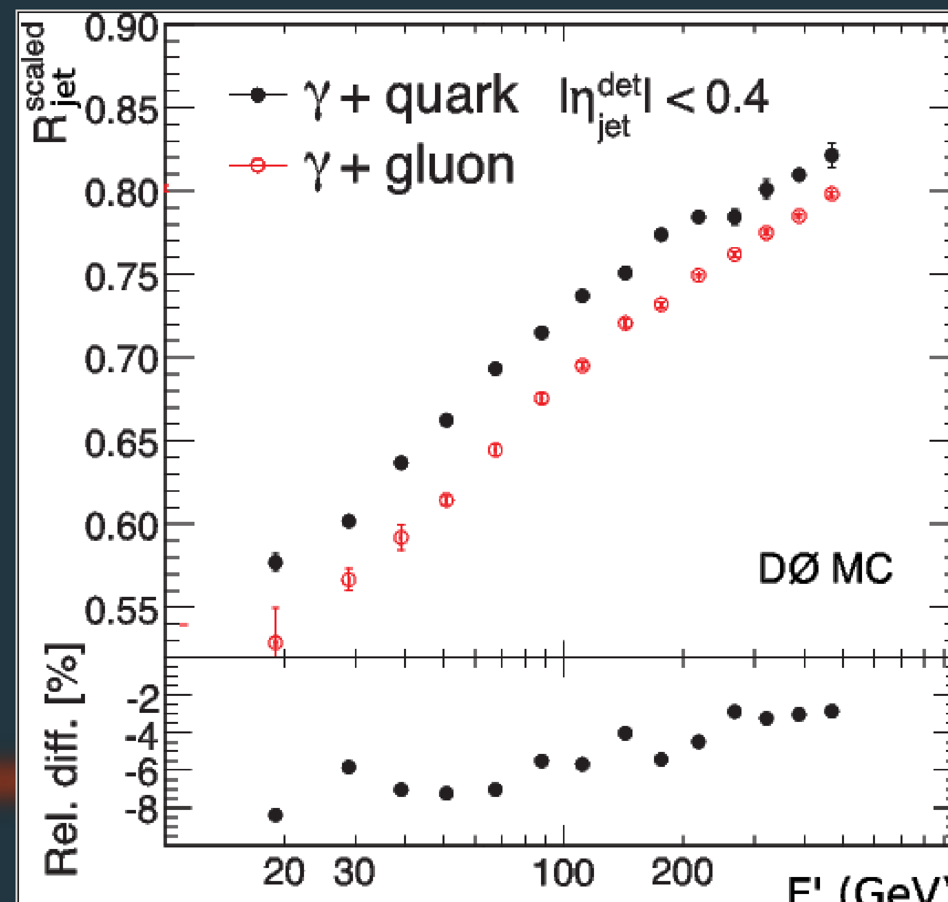
Jet energy calibration

$$E_{\rm jet}^{\rm ptcl} = \frac{E_{\rm jet}^{\rm meas} - O}{F_\eta \cdot R \cdot S} \cdot k_{bias}$$

Multistage correction
- large data sets to map out detector features
- finely tuned MC to extrapolate measurements
- careful determination of physics and instrumental biases

Example: flavor dependence in jet response.

Large effect may have unexpected consequences if not carefully considered (at least on average)

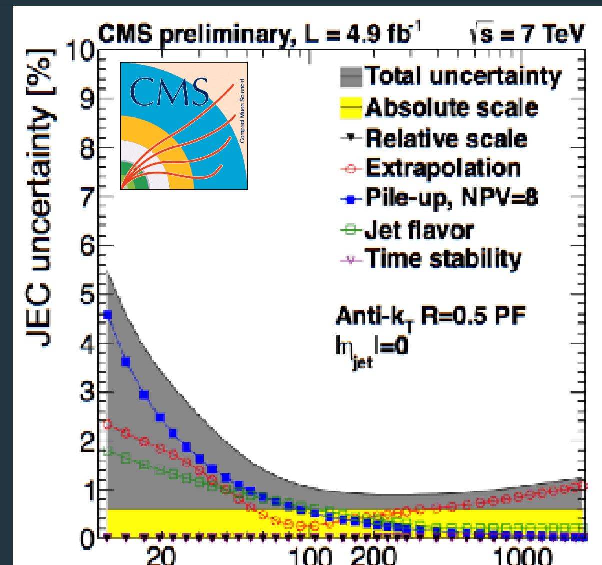


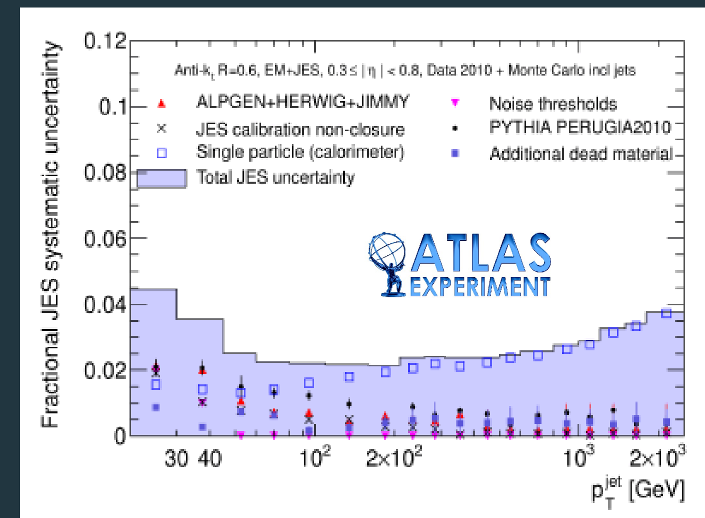
Jet energy calibration

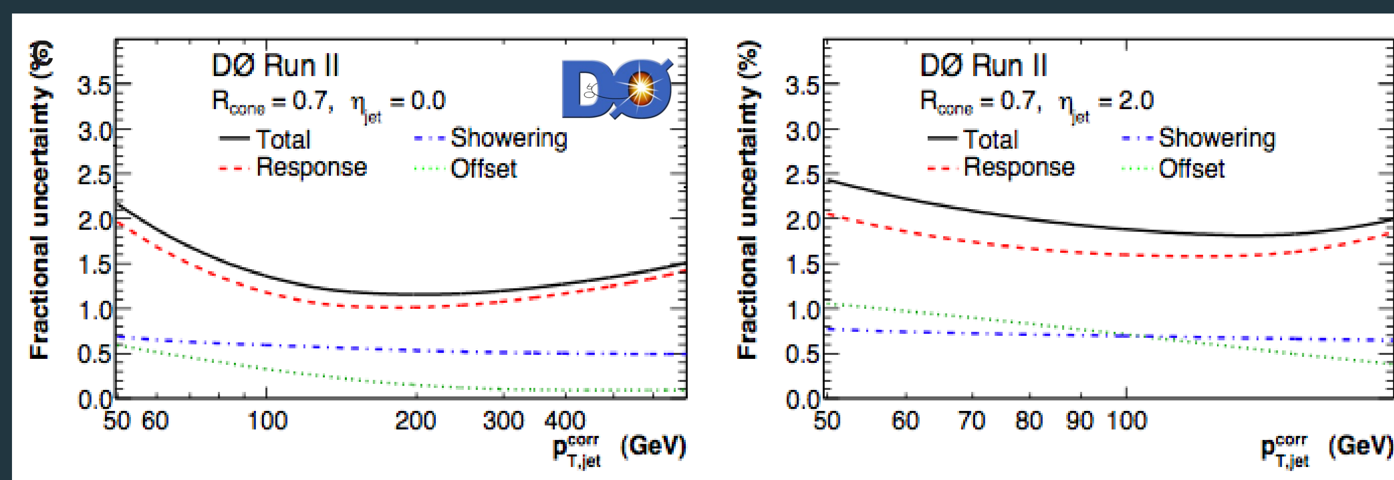
Very challenging experimental issue to determine precise JES

LHC experiments making tremendous progress, already approaching Tevatron level of ~1-2%

=> precision measurements possible

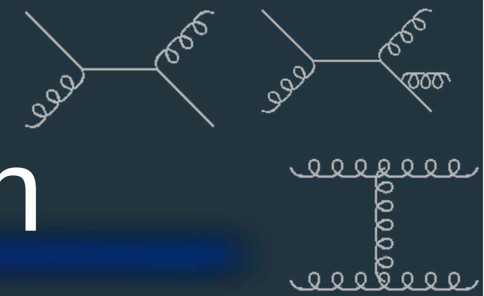






$$\frac{d^2\sigma^{\text{jet}}}{dp_T\,dy}$$

Inclusive Jet Production

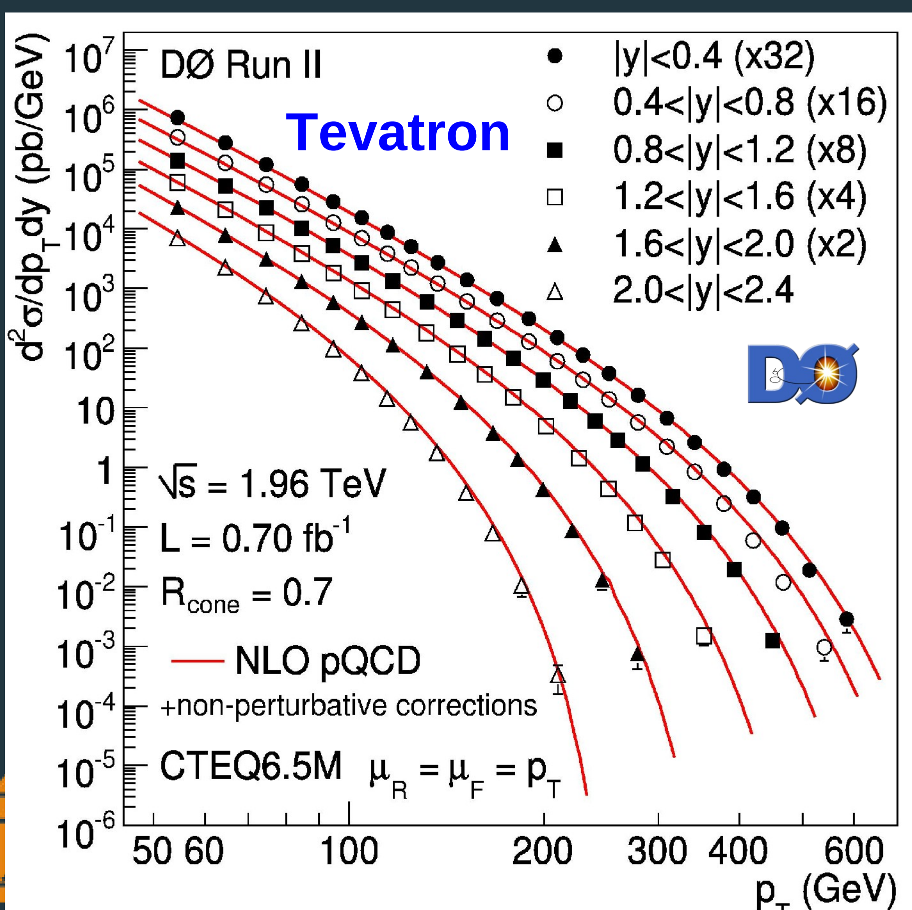


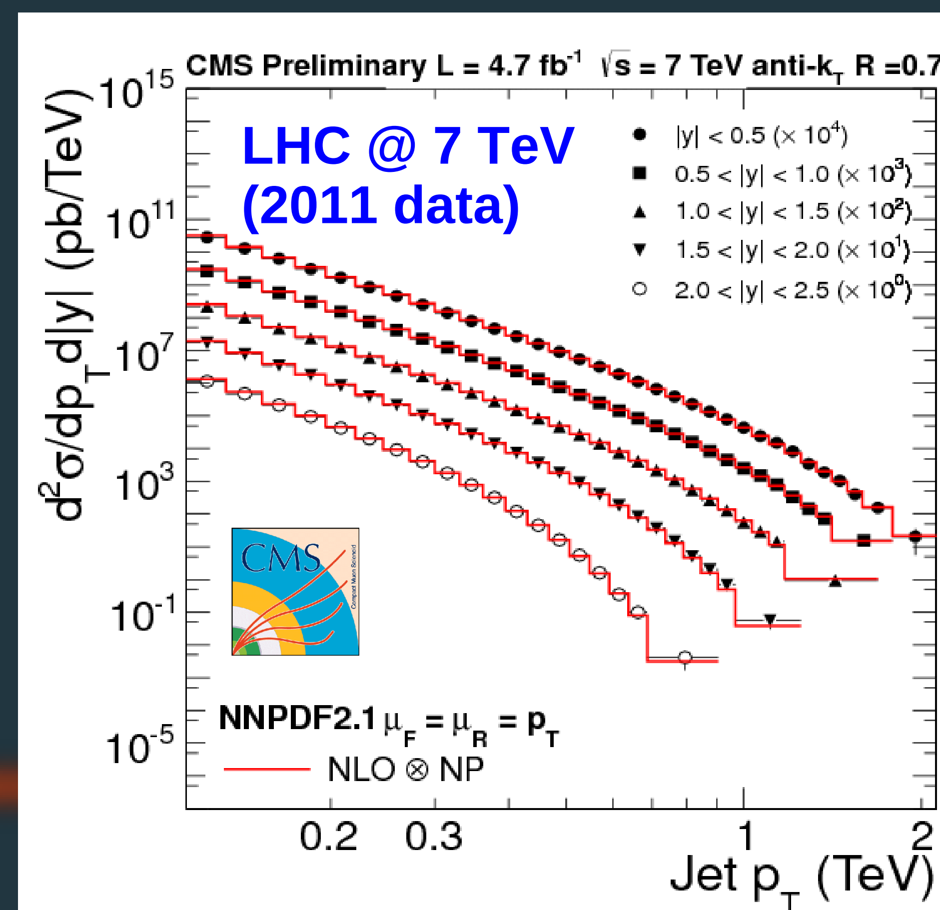
etc

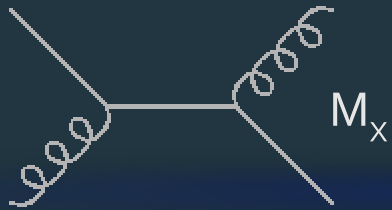
One of the most elementary measurements at hadron colliders.

Count events with >=1jet satisfying p_T,y requirements

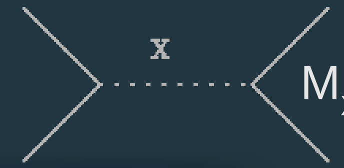
Inclusive jet cross sections at Tevatron/LHC provide strong tests of PDFs and pQCD over 8-9 orders of magnitude up to 2 TeV



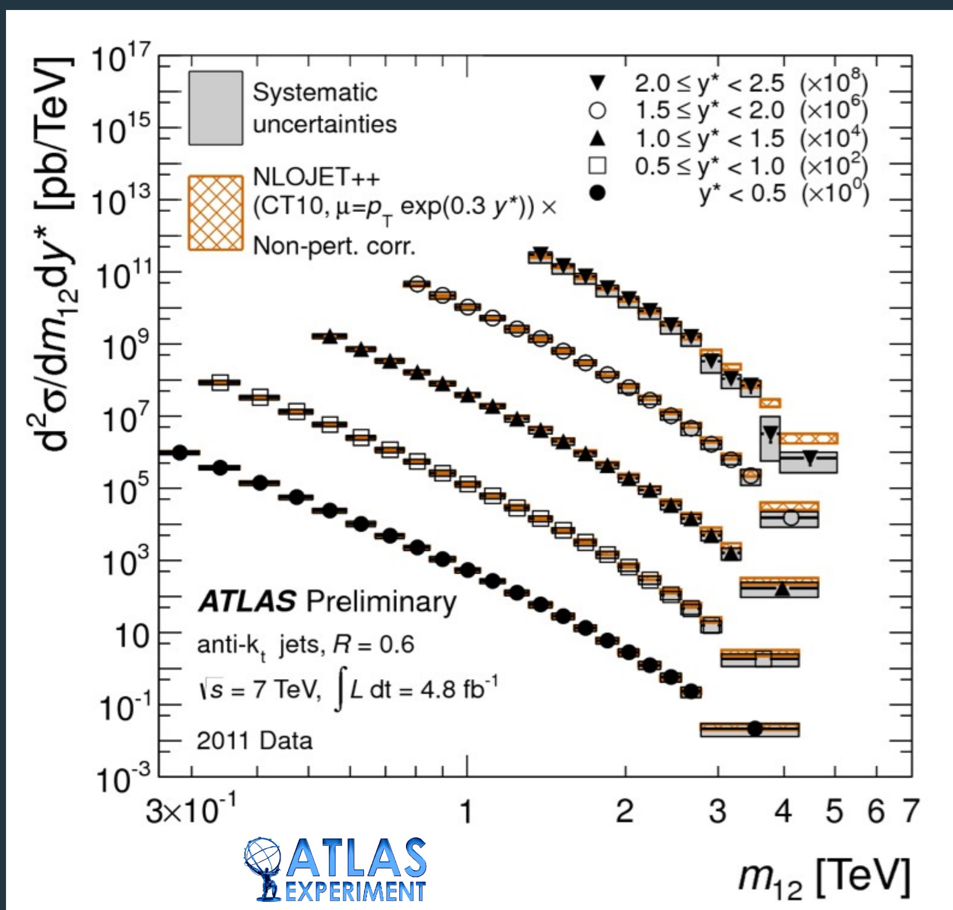


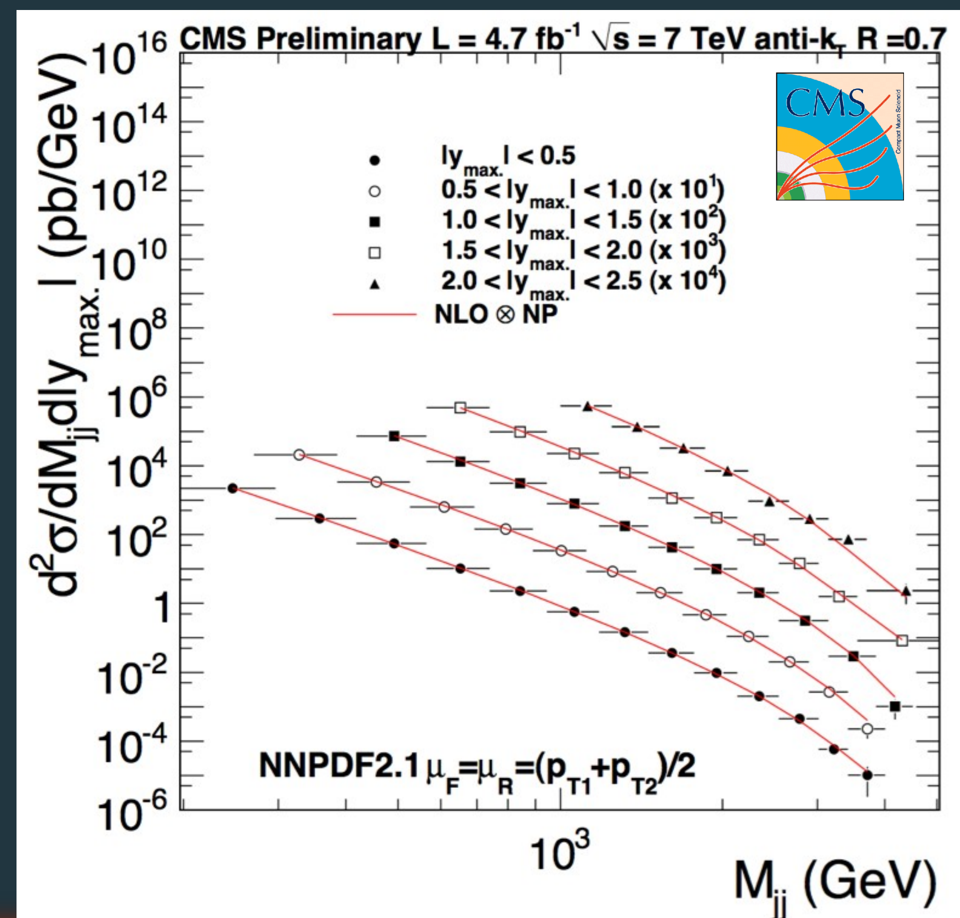


Dijet mass

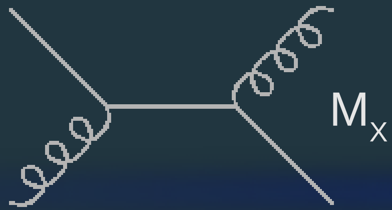


With ~5/fb per experiment of 2011 data, jet physics extended to the TeV range
Dijet mass leads the way in highest energy reach, with highest masses ≥4 TeV
Excellent confirmation of perturbative QCD up to the very highest scales!





CMS: CMS PAS QCD-11-004
Atlas: arXiv:1112.6297



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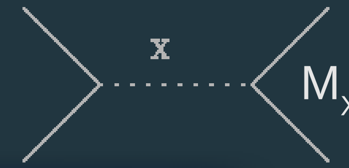

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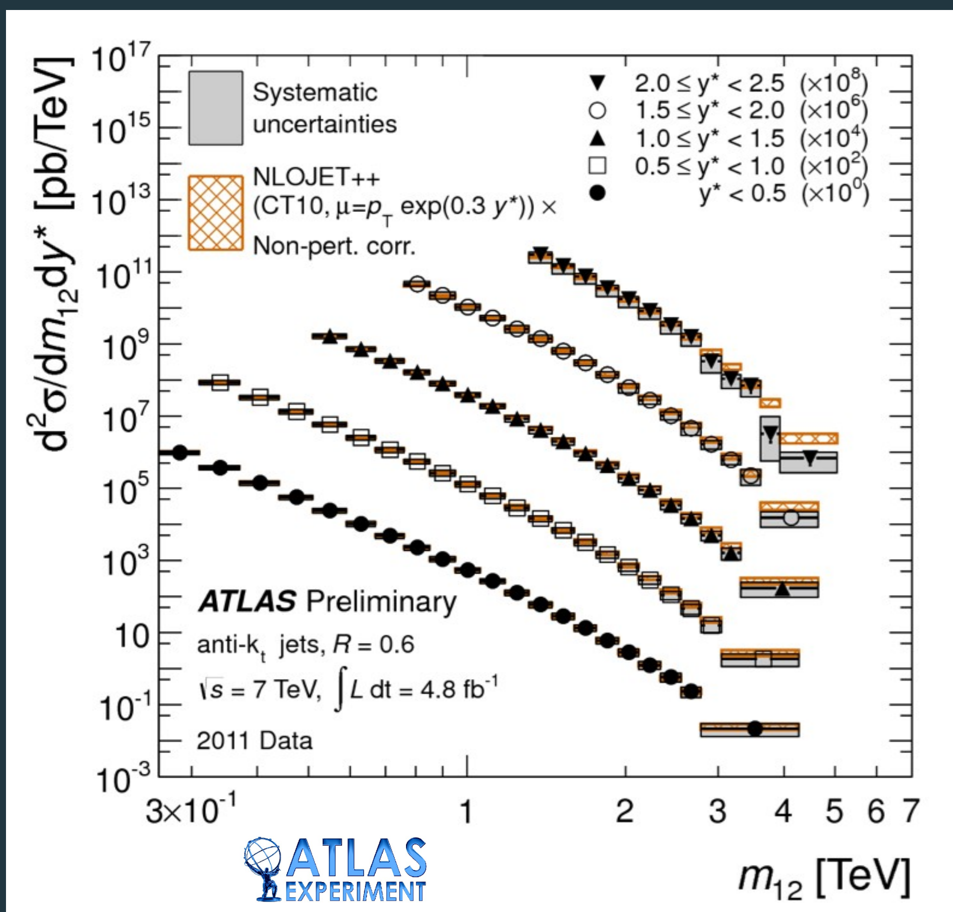

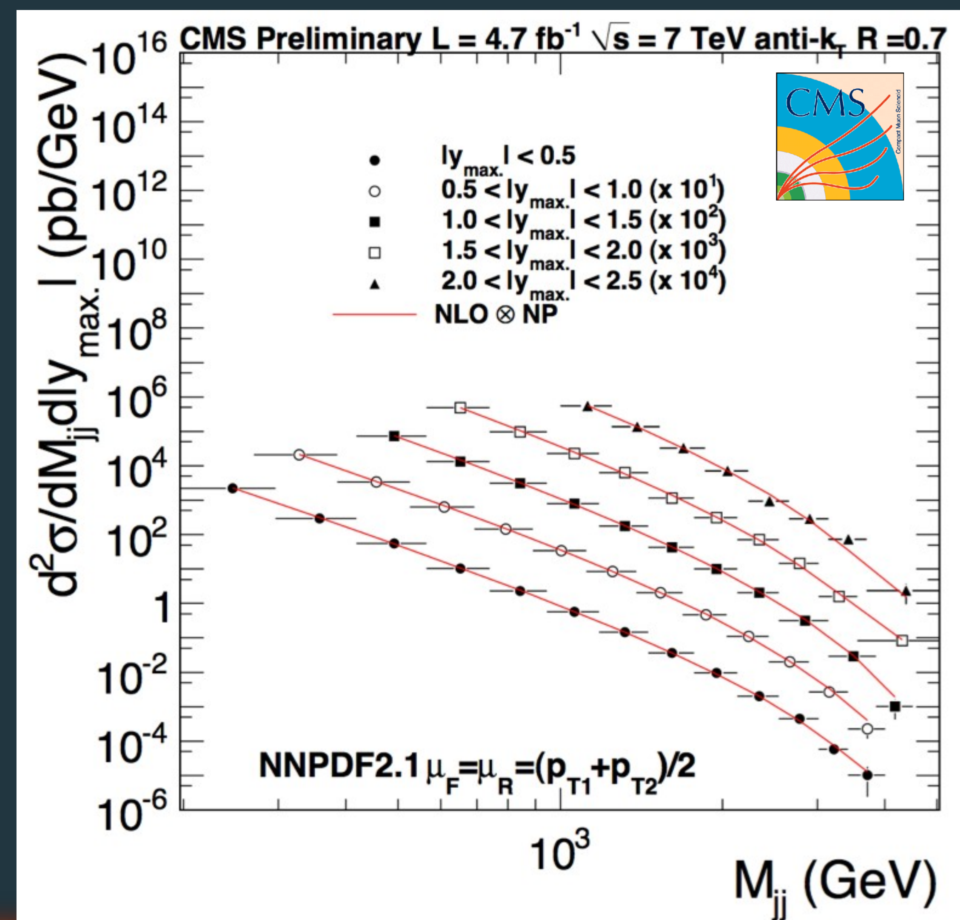

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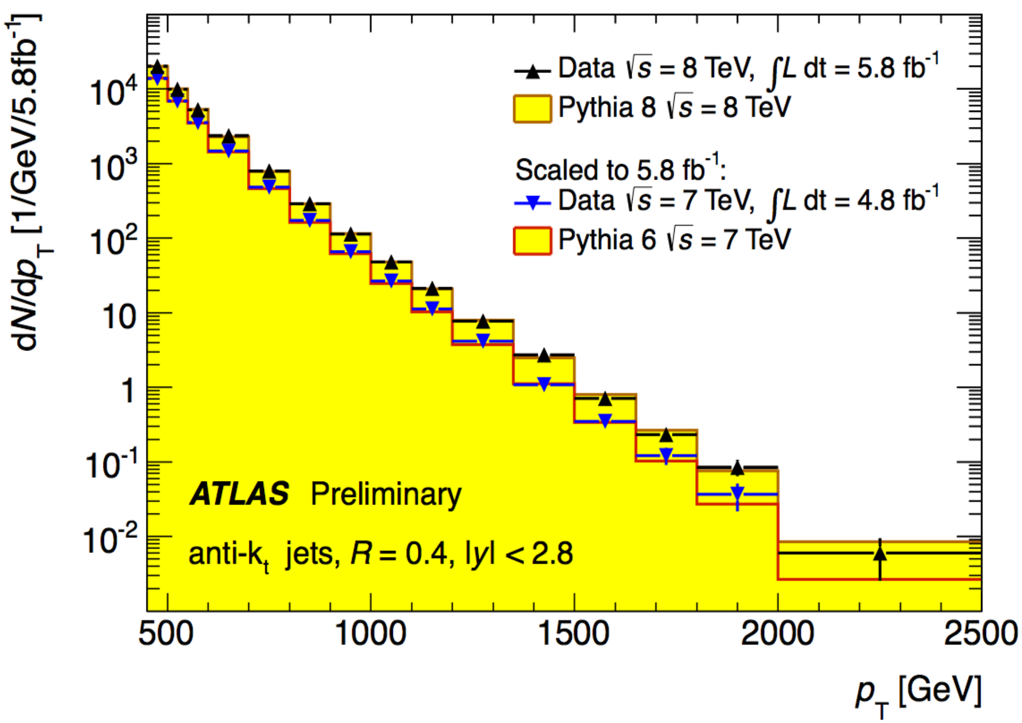
*good/bad news!

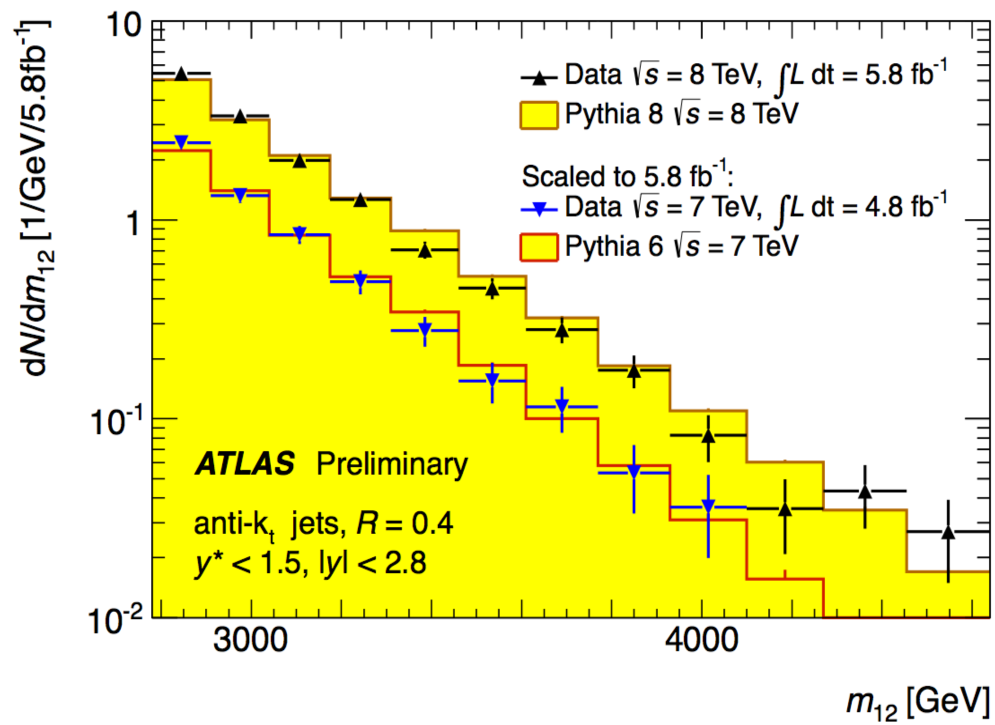
First 8 TeV jet data

LHC @ 8 TeV

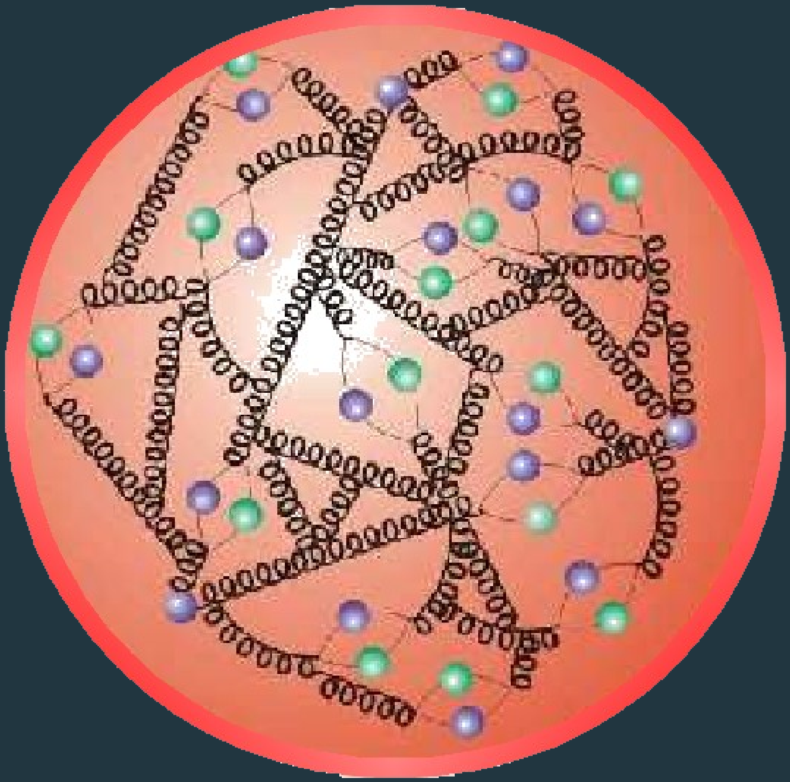
Inclusive jet pT and dijet mass spectra at $\sqrt{s}$ = 8 TeV (5.8 fb^{-1}) for anti-kt R=0.4 jets

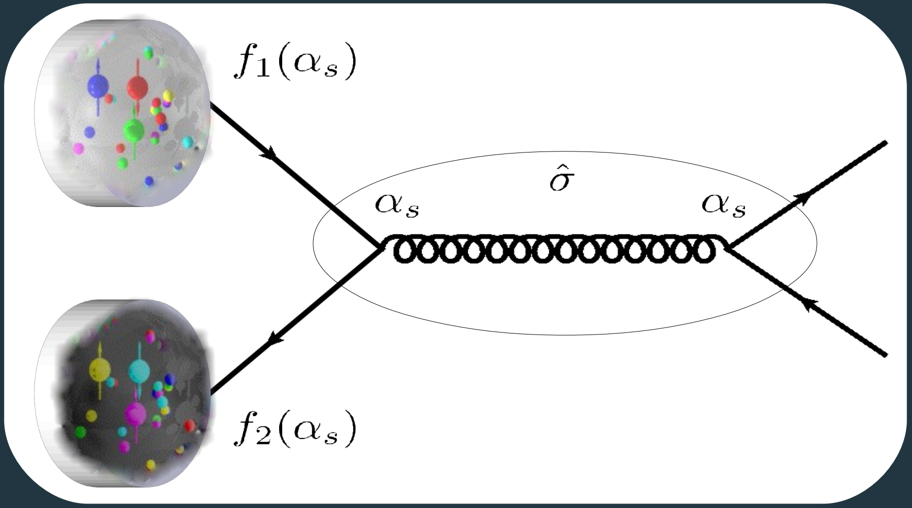
Comparison with 7 TeV 2011 data (4.8 fb^{-1}) and to Pythia 6(8) MC predictions.
=> cross sections increase at larger center of mass energy, as expected
=> even higher energy coverage at 8 TeV





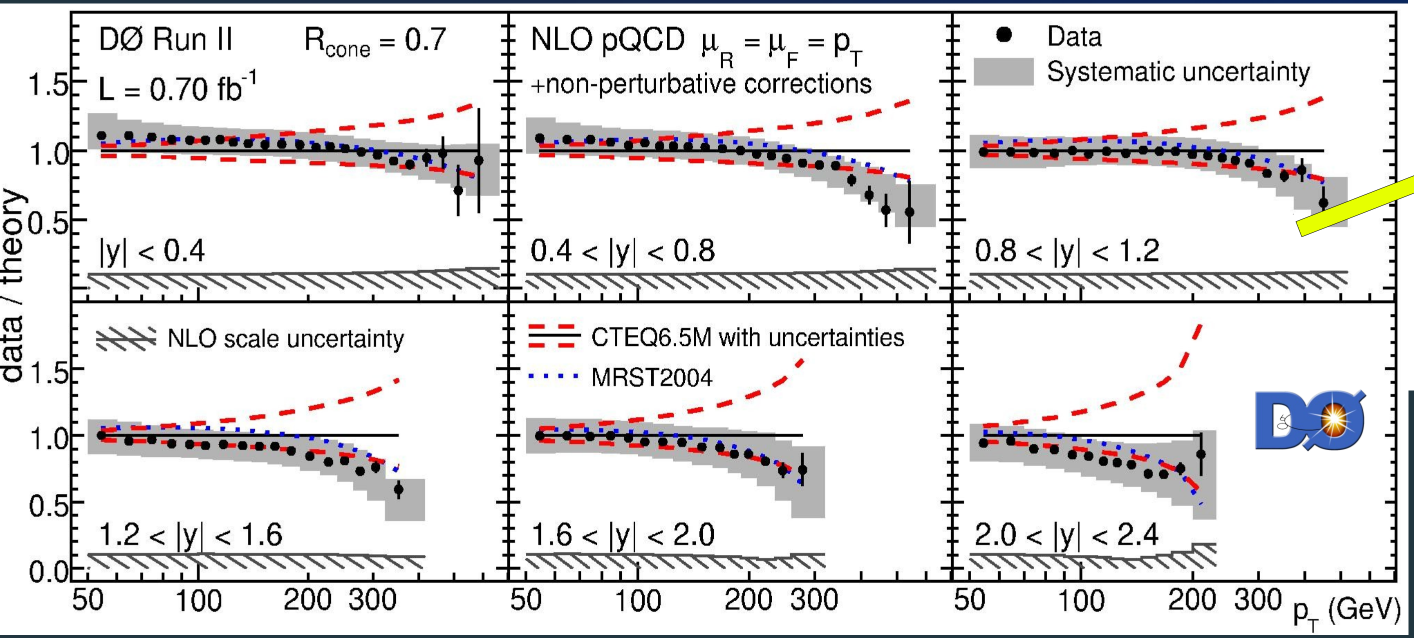
Examining the proton

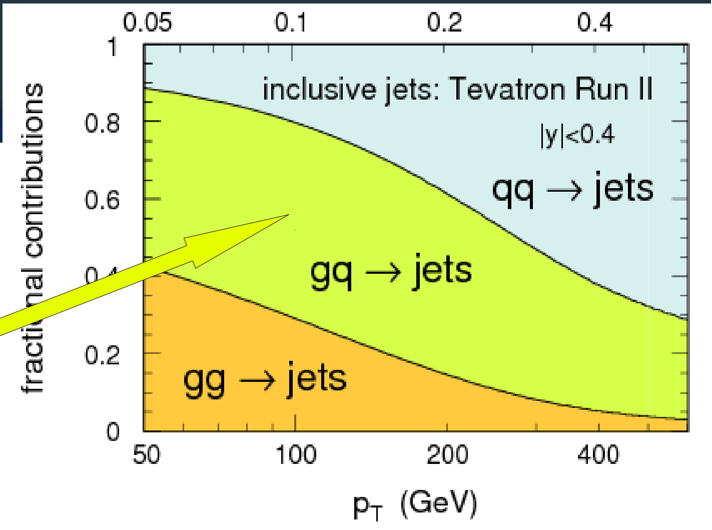




Tevatron

Constraints on PDFs





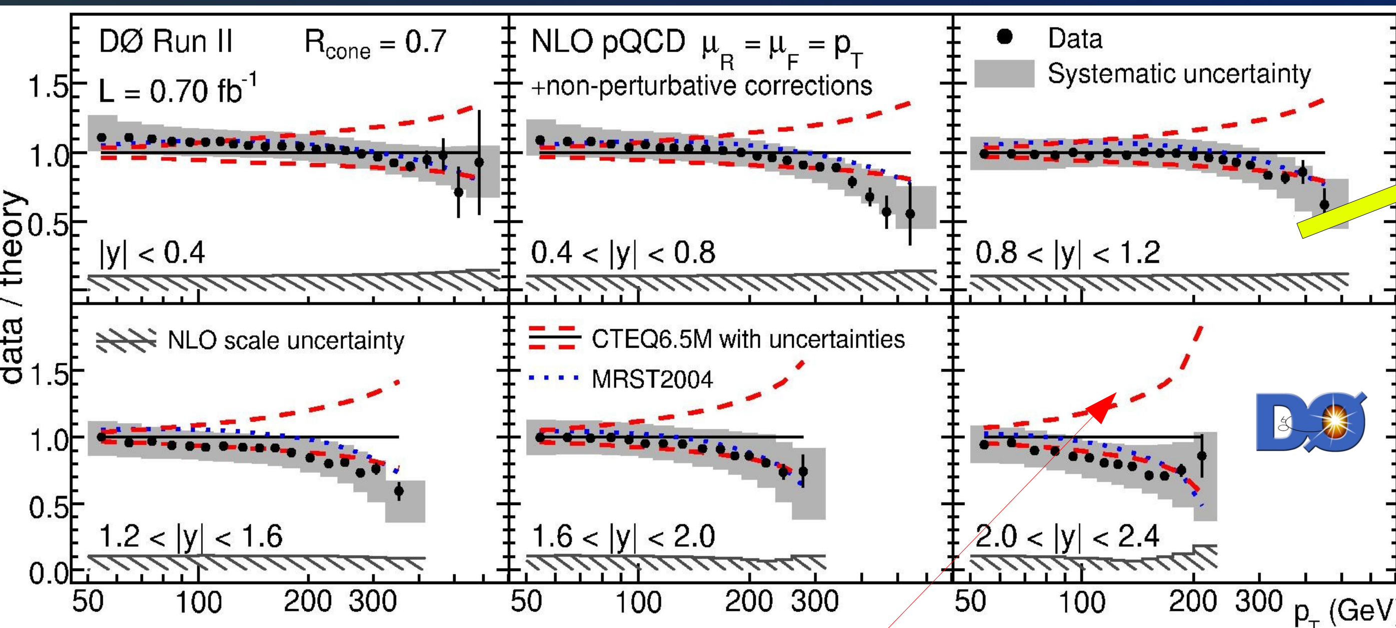
Breakdown of partonic initial states

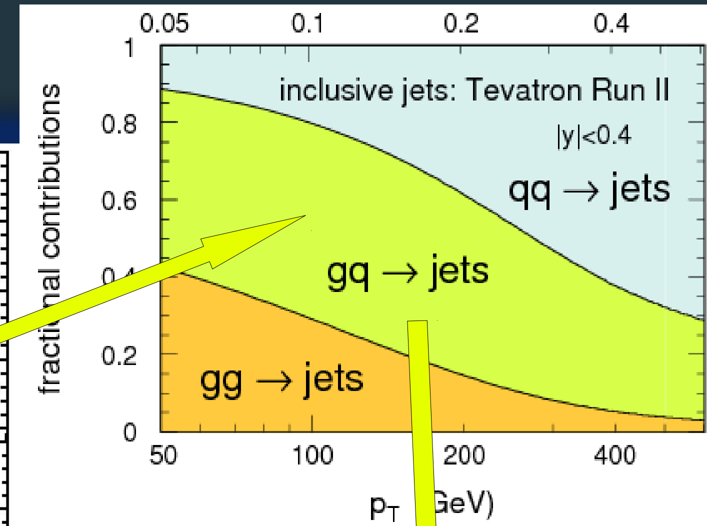
PRD75, 092006 (2007), PRL 101, 062001 (2008), PRD85, 052006 (2012)

D0 inclusive jet measurements: data/theory

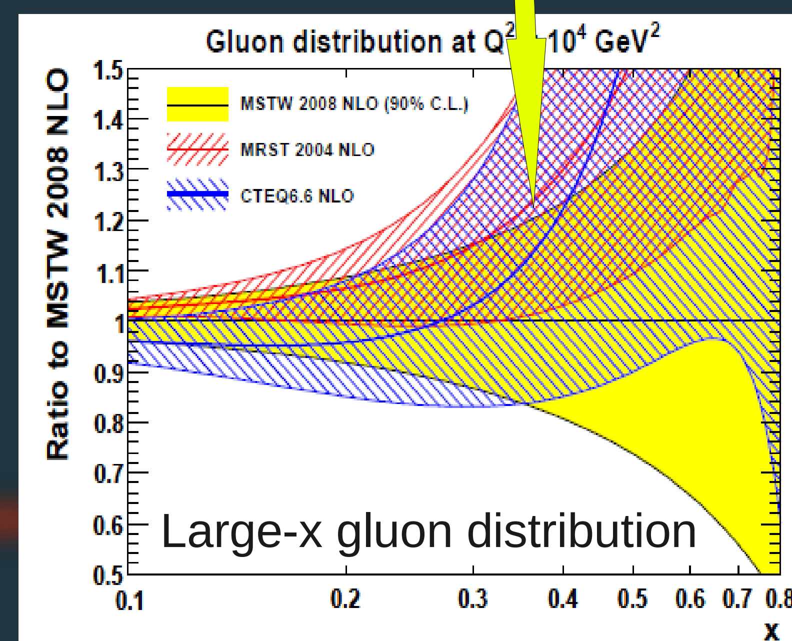
Tevatron

Constraints on PDFs





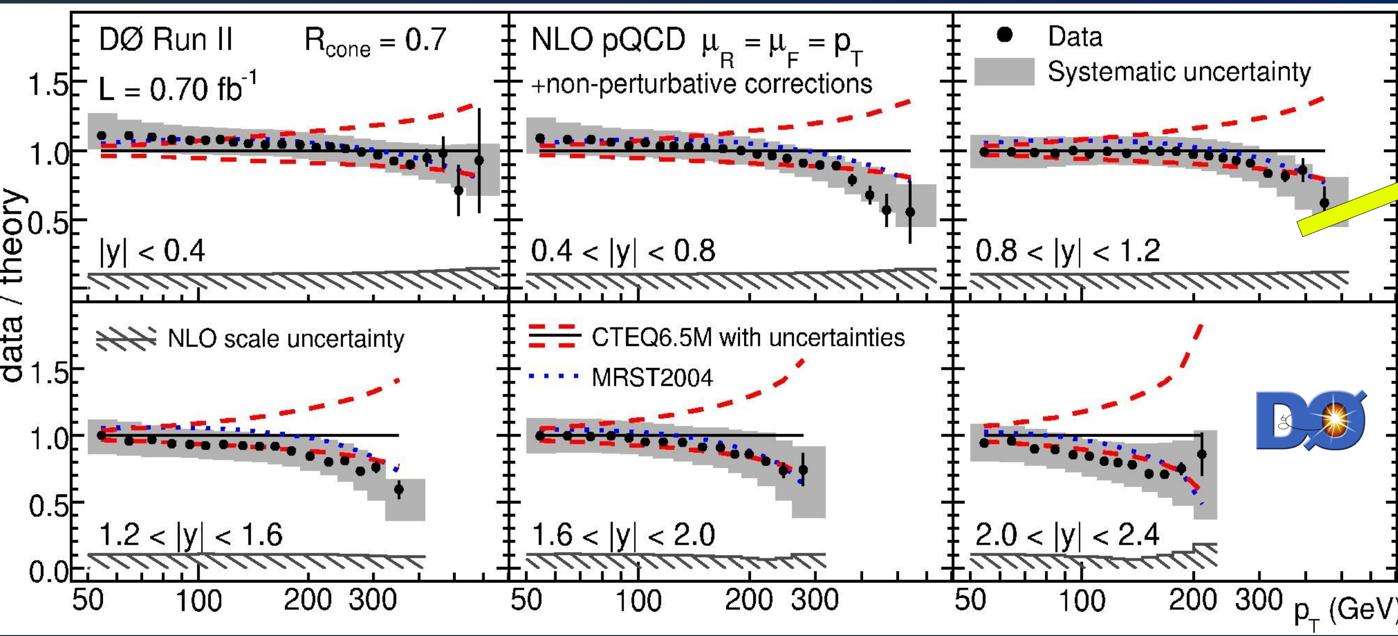
PRD75, 092006 (2007), PRL 101, 062001 (2008), PRD85, 052006 (2012)

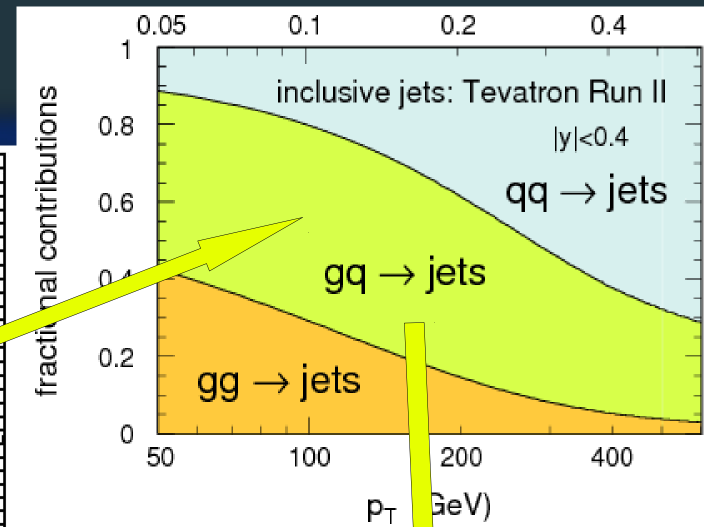


Experimental uncertainties at high pT are lower than theoretical (largely PDF ones):
=> constrain PDF models

Tevatron

Constraints on PDFs





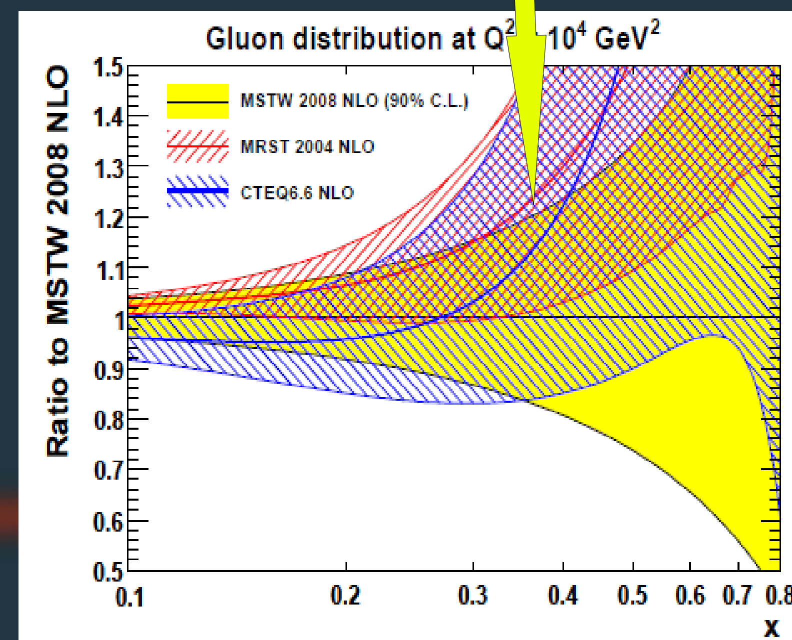
PRD75, 092006 (2007), PRL 101, 062001 (2008), PRD85, 052006 (2012)

Experimental uncertainties at high pT are lower than theoretical (largely PDF ones):
=> constrain PDF models

D0&CDF jet data favored lower bound of the theoretical (CTEQ6.5M PDF) predictions, with smaller gluon content at high x.

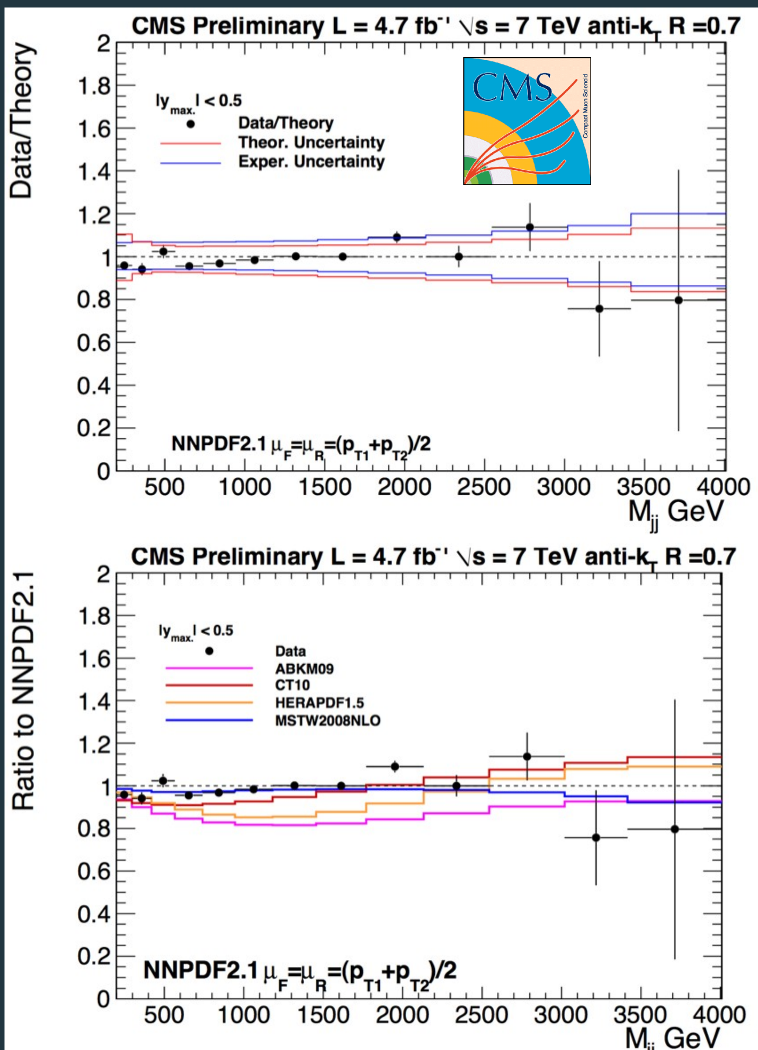
Tevatron measurements modified gluon PDF (especially at x>0.25) & reduces PDF uncertainties.

MSTW 2008(+) uses CDF kT and D0 cone results.



Constraints on PDFs (LHC)

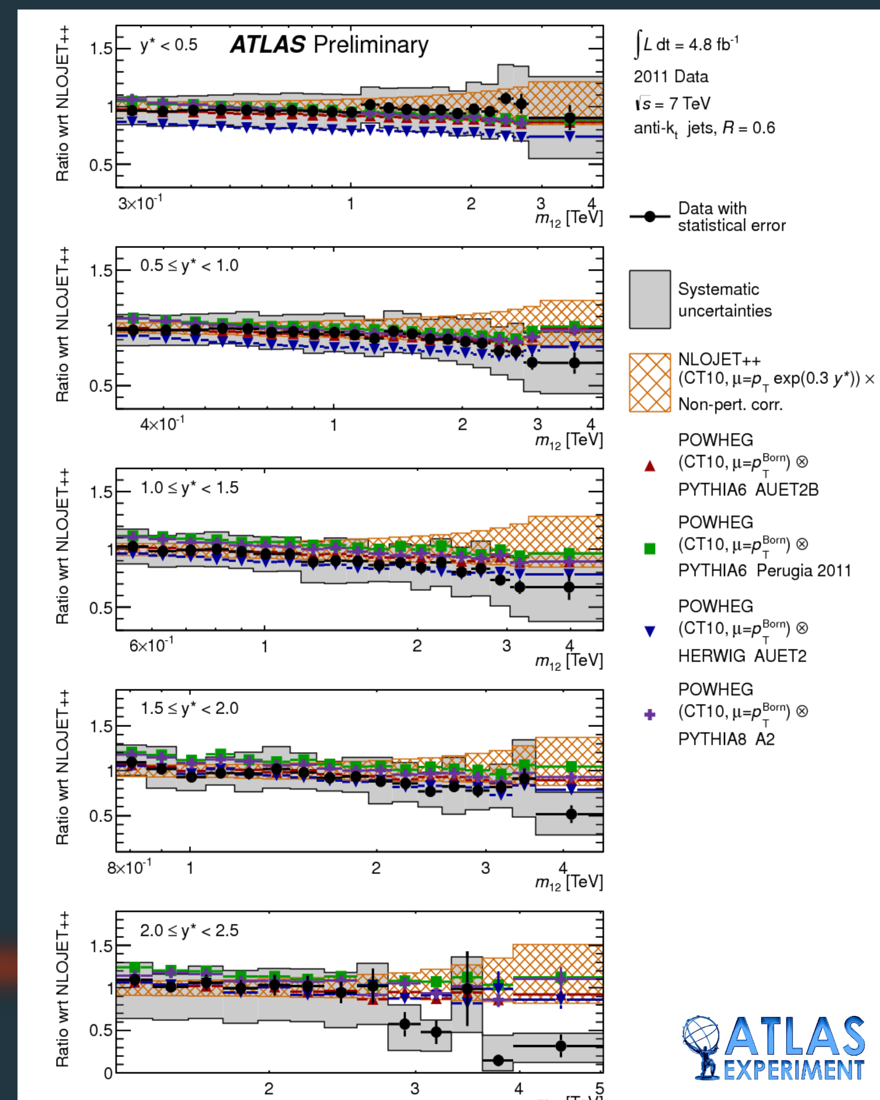
– LHC data analyses at 7 TeV are reaching precision to constrain PDFs
– Total experimental uncertainties are close to theoretical ones
=> Should have future input to further constrain PDFs



Overall good agreement with theory (NLOJET++ and POWHEG+PS)

Large disagreement at very high M_{12} and y*

(y* = |y1 -y2|/2)



PDF Sensitivity

$$\frac{d^2\sigma^{\text{jet}}}{dp_T dy}$$

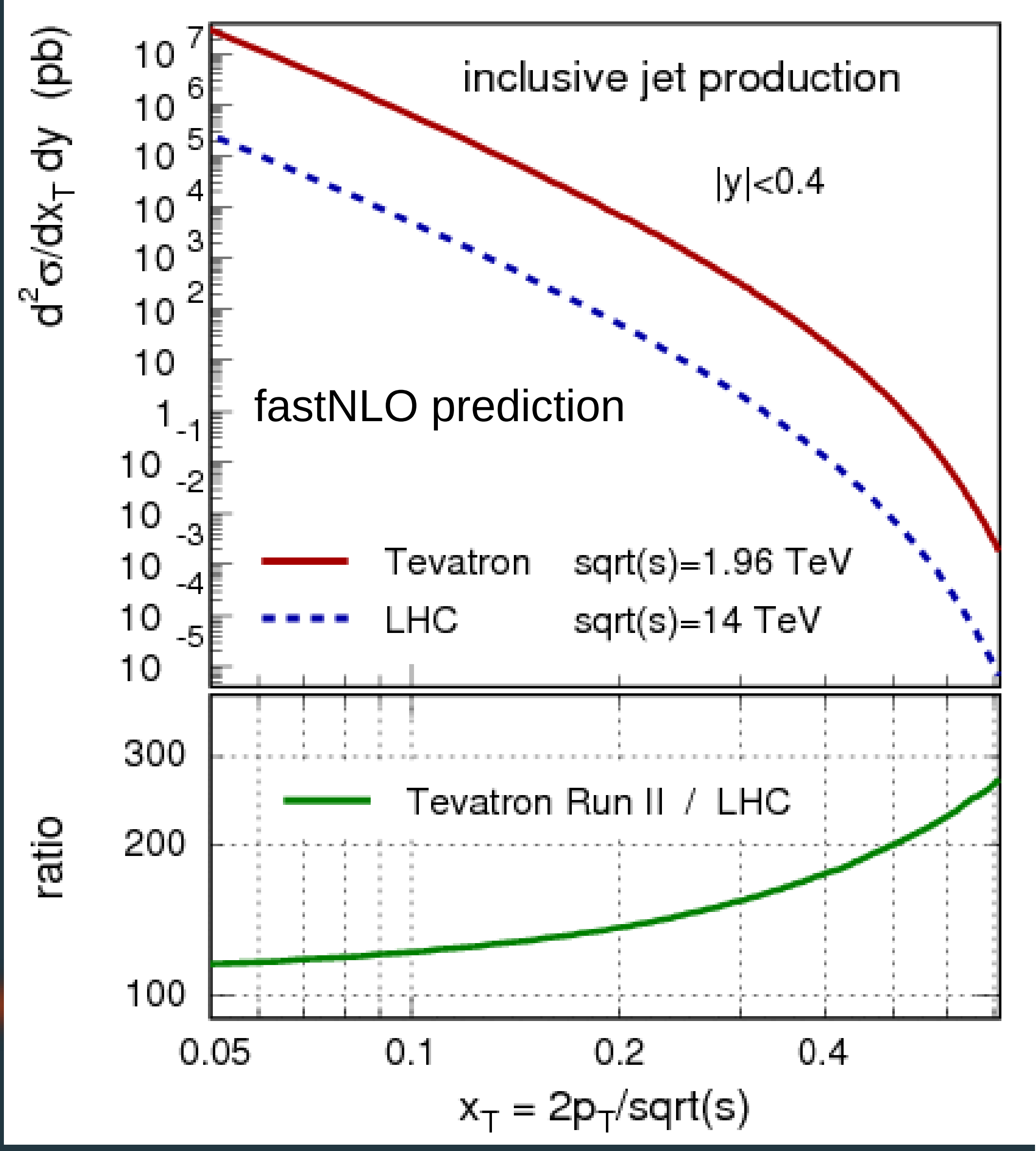
LHC experiments cover larger phase space in jet pT and |y| than Tevatron (probe down to x~0.5x10^{-3}, well studied earlier by DIS) but still have less sensitivity at high x.

- compare jet cross section at fixed $x_T = 2\ p_T$ / sqrt(s)

Tevatron (ppbar)
>100x higher cross section @ all x_T
>200x higher cross section @ x_T >0.5

LHC (pp)

- need more than 2000 fb^{-1} luminosity to improve Tevatron@10 fb^{-1}
- more high-x gluon contributions
- but more steeply falling cross sect. at highest p_T (=larger uncertainties)

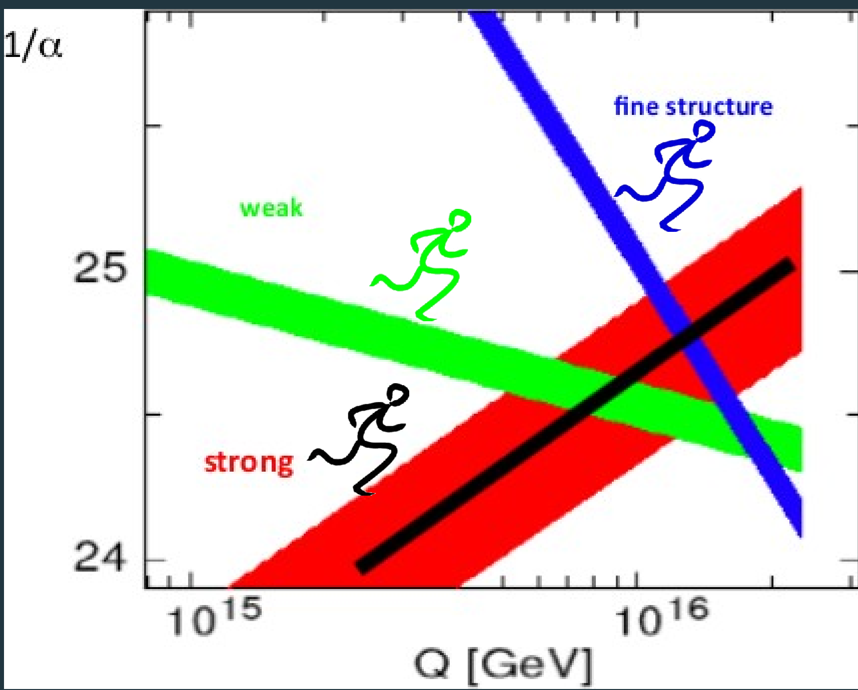


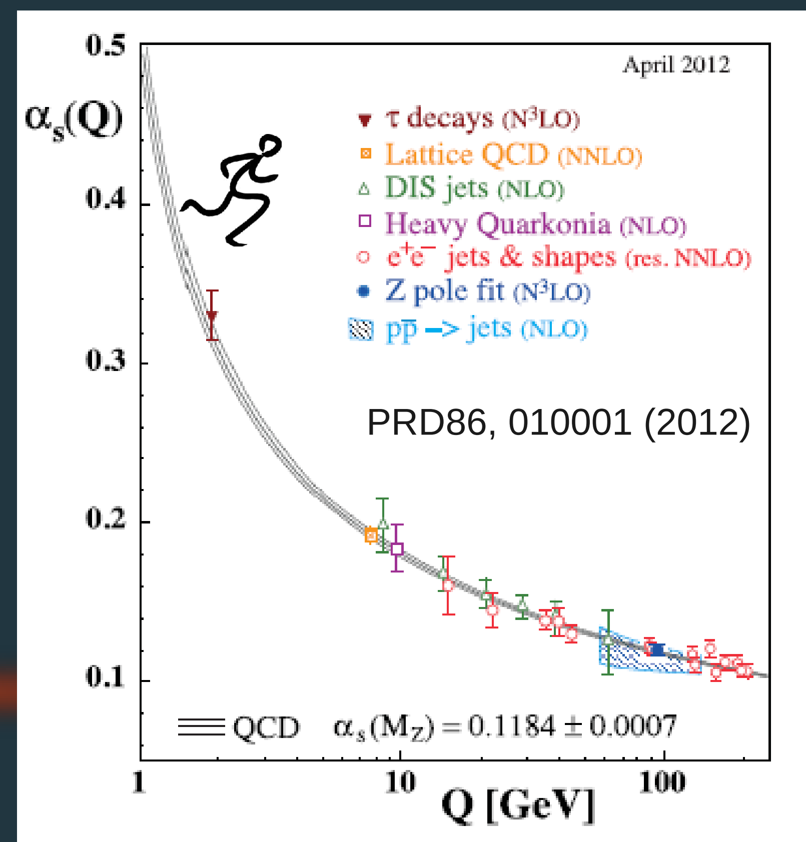
Strong coupling constant, α_s

- least known of the couplings ($\triangle\alpha_S$ (WA) = 0.6%)
- translates into uncertainty on PDFs and hadronic cross sections
- has influence on GUT

Renormalization Group Equation relates α_s values at different scales (Q)

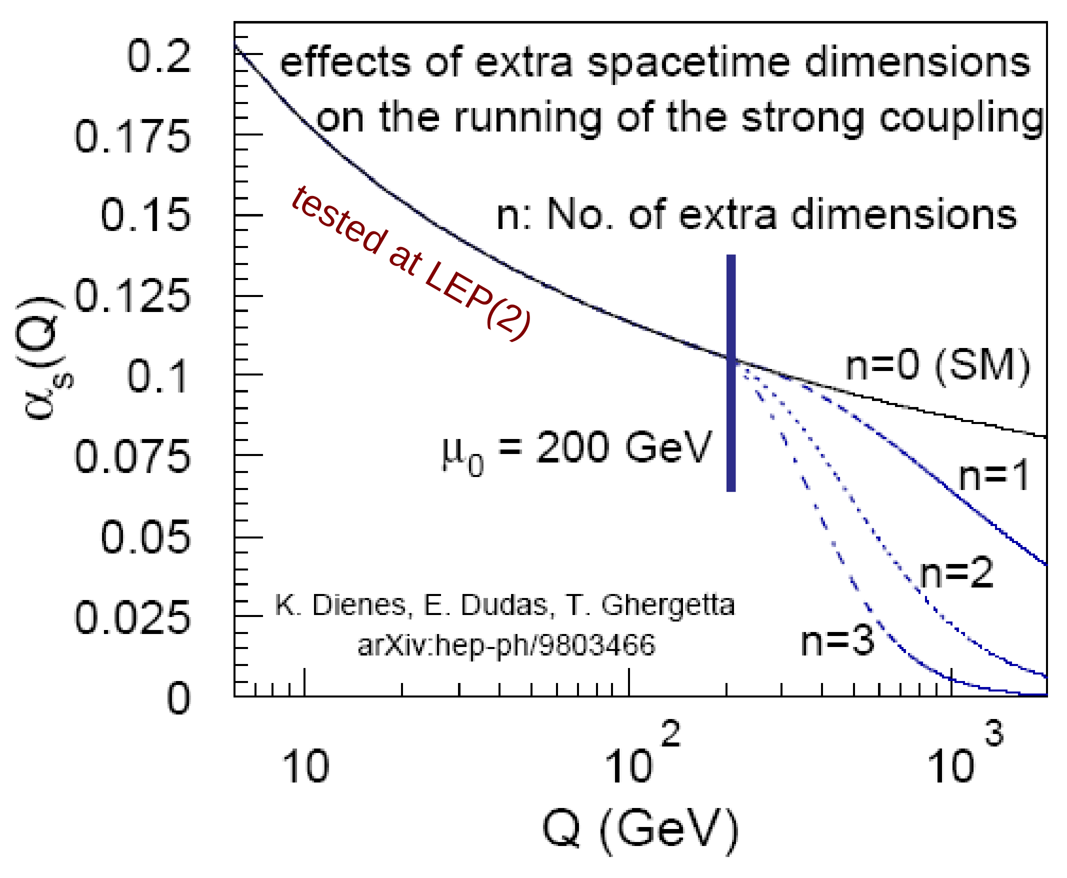
Tested at LEP, HERA up to Q ≈ 208 GeV, recently by DØ (54-145 GeV)





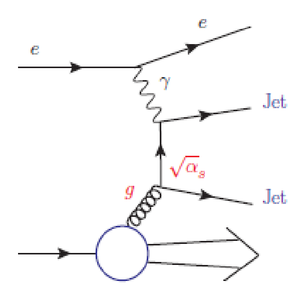
Strong coupling constant, α_s

Running of $\alpha_s(Q)$ could be modified for large Q, e.g. by extra dimensions
=> should be tested using variable free of RGE (PDF) dependence

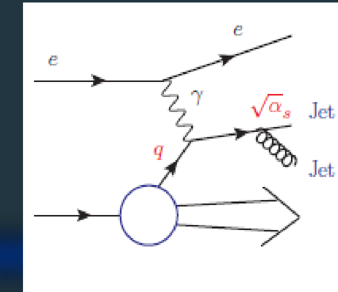


Above some scale μ_0, appearance of extra spacetime dimensions can accelerate "running" of the gauge couplings.

Jet data allows extraction of α_s (and therefor tests of RGE) at large Q values



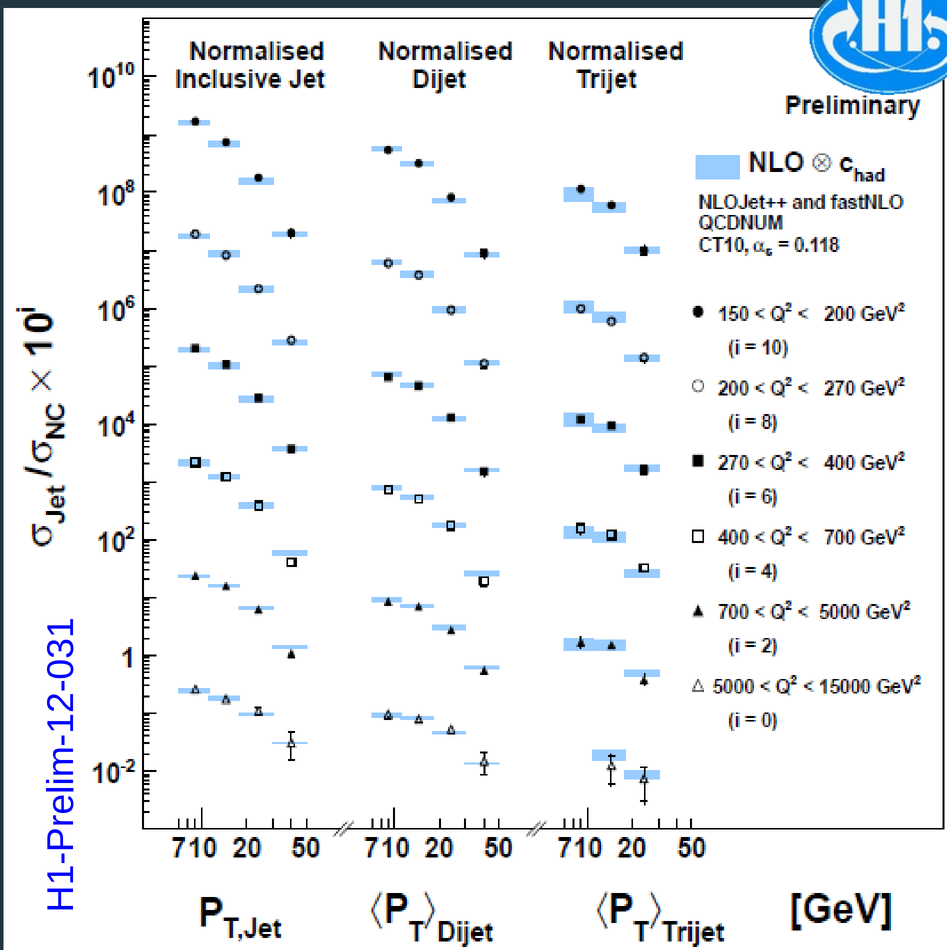
Jet in DIS (HERA)



- Inclusive jet, 2-jet, 3-jet productions
- first double-diff. 3-jet measurement at high Q^2
- data are well described by NLO

=> used to extract α_S

Normalized multijet cross section



Normalized inclusive jets:

$$\alpha_s(M_z)=0.1197\pm0.0008(\exp)\pm0.0014(PDF)\pm0.0011(had)\pm0.0053(theor)$$

Normalized Dijets:

$$\alpha_s(M_z)=0.1142\pm0.0010(\exp)\pm0.0016(PDF)\pm0.0009(had)\pm0.0048(theor)$$

Normalized Trijets:

$$\alpha_s(M_z)=0.1185\pm0.0018(\exp)\pm0.0013(PDF)\pm0.0016(had)\pm0.0042(theor)$$

Simultaneous fit to cross-section measurements (42 points):

$$\alpha_s(M_z)=0.1163\pm0.0011(\exp)\pm0.0042(theor)$$

Uncertainties: ±0.9% (exp), ±1.2% (PDFs), ±0.7% (hadr), ±3.4% (HO), ±3.8% (total)

Theor. uncertainties are dominating

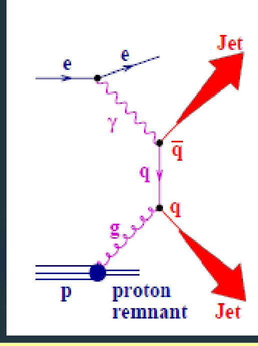
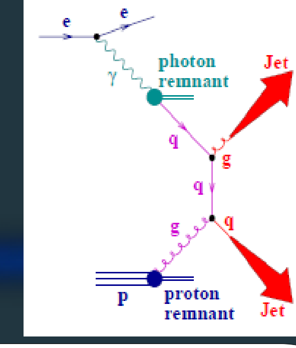
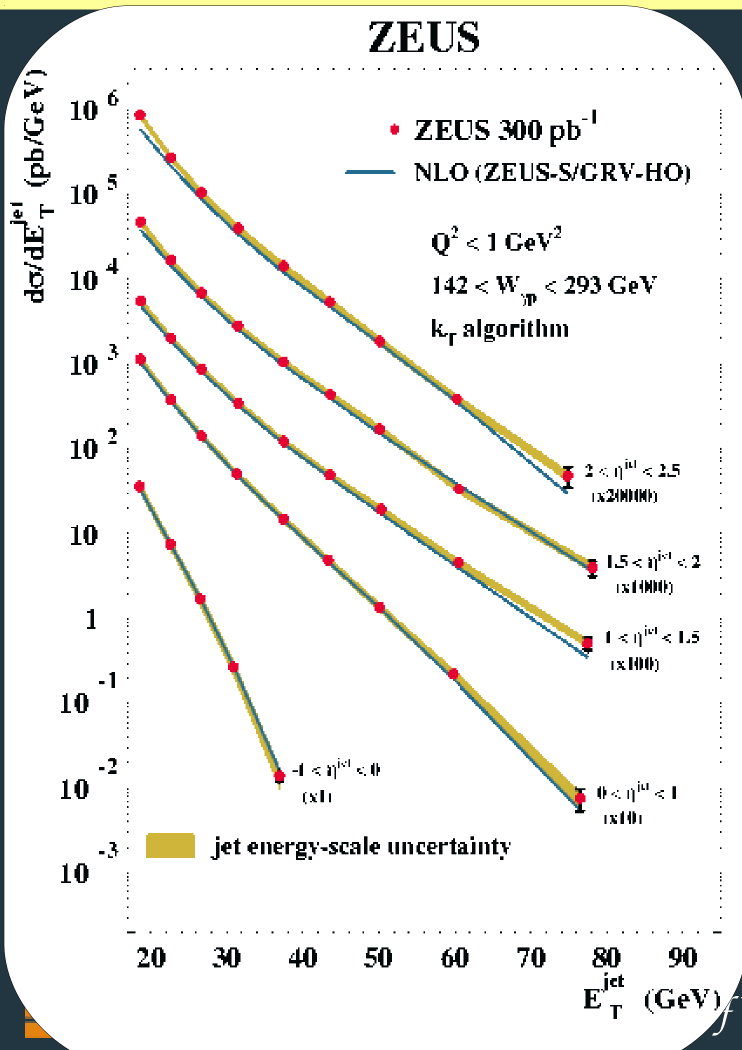


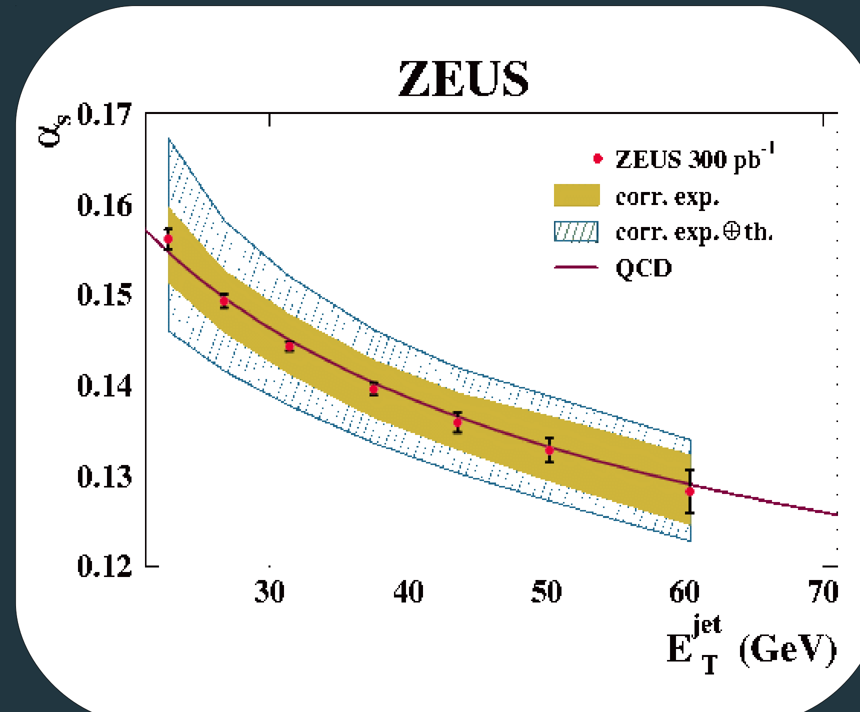
Photo production

Jets in PHP



Measurements of jet cross sections in photoproduction:
– test of pQCD, photon and proton SFs
– determination of α_s





- Good description of data by NLO (except very low/high Et, high η)

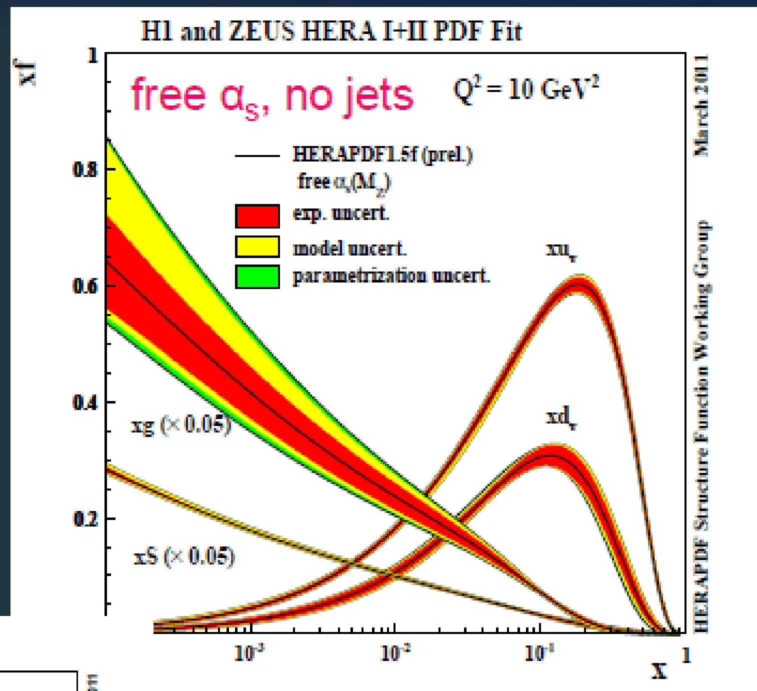
- repeated with different jet algorithms
=> consistent result
=> similar precision

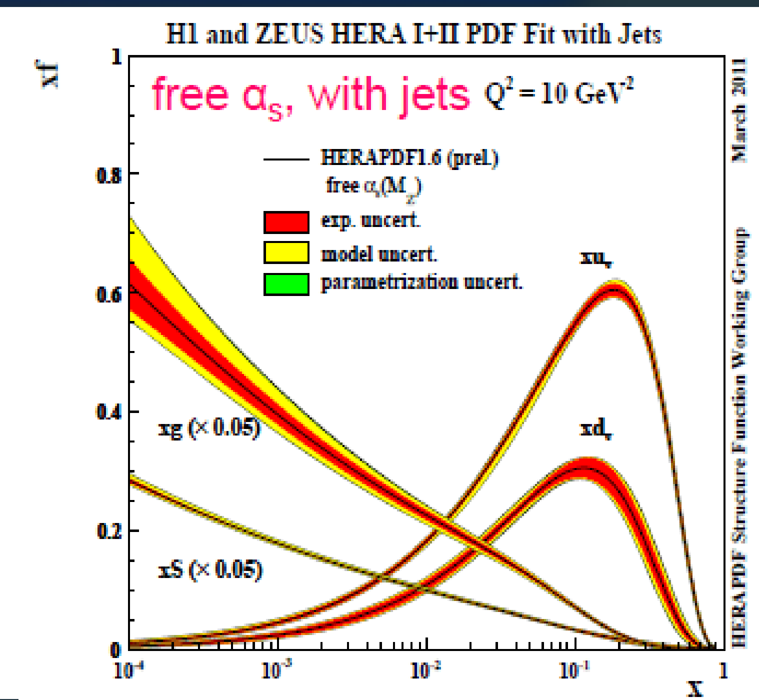
– α_s is extracted from cross sections at $21 < E_t^{jet} < 71$ GeV:

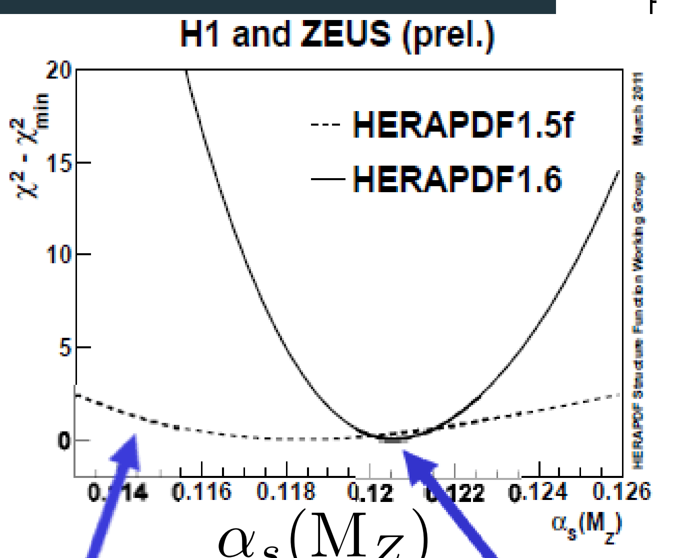
$$\alpha_s(M_z) = 0.1206^{+0.0023}_{-0.0022}(\exp)^{+0.0042}_{-0.0035}(theor)$$

(pPDF: 1%, γPDF: 1-2%)

Combined PDF Fit and α_S at HERA







=> PDF fit of inclusive DIS data: free αs leads to very large uncertainty on gluon density

=> including jet DIS data dramatically decreases low-x gluon uncertainty

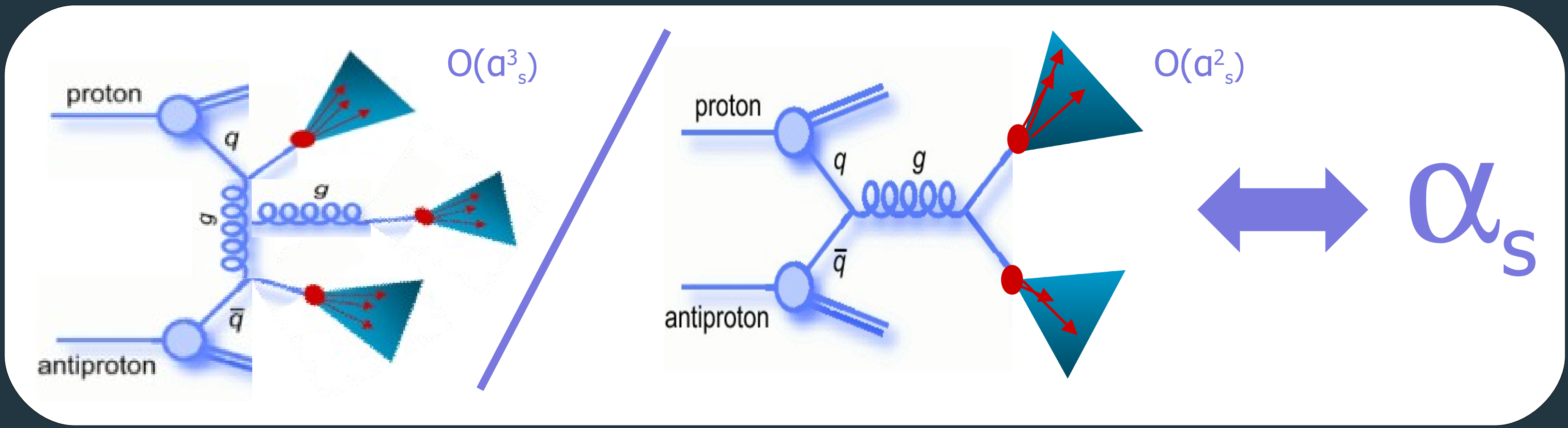
=> adding jet DIS data reduces correlation of α_S and gluon PDF

$$\alpha_s(M_z) = 0.1202 \pm 0.0019(\exp + mod + hadr)^{+0.0045}_{-0.0036}(scale)$$

Introducing $R_{\Delta R}$

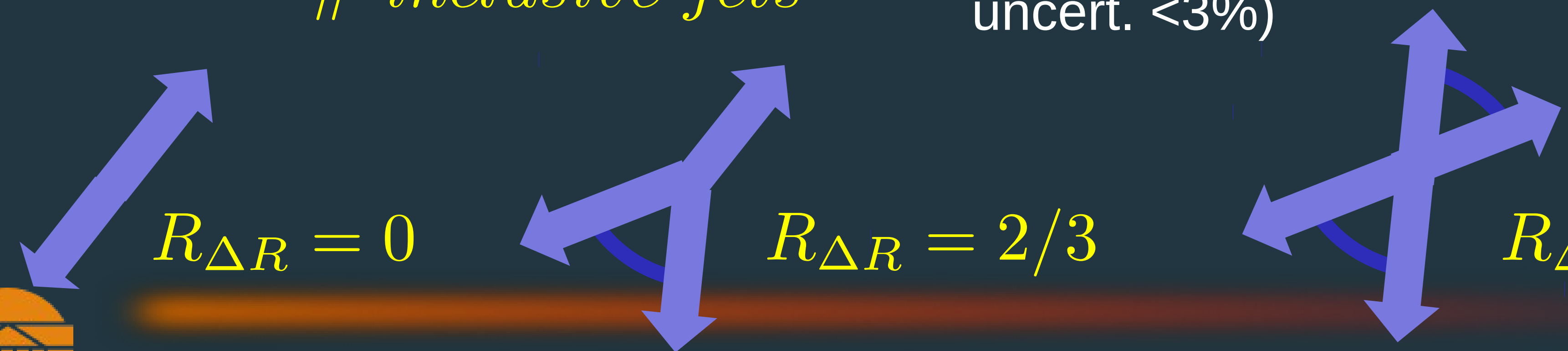
Latest from Tevatron

Angular/ratio variable: average number of neighboring jets above some p_T threshold within a given ΔR interval

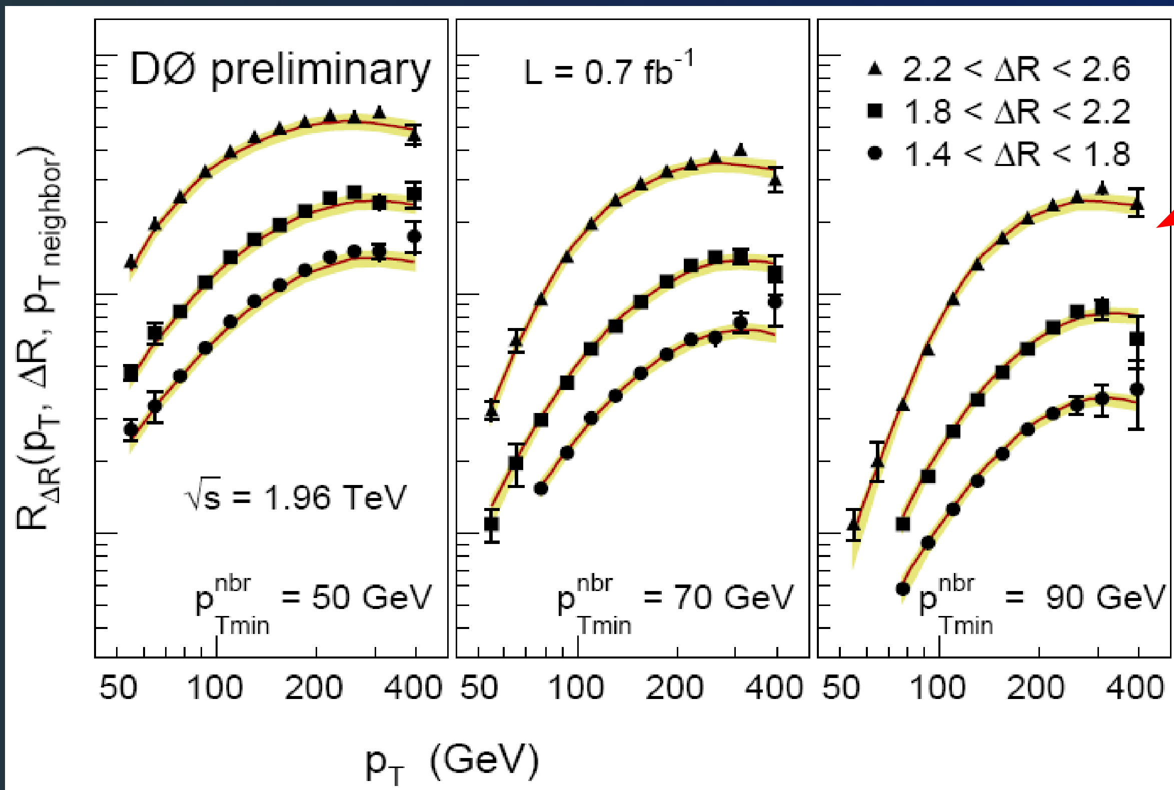


$$R_{\Delta R} = \frac{\#\ of\ neighboring\ jets}{\#\ inclusive\ jets}$$

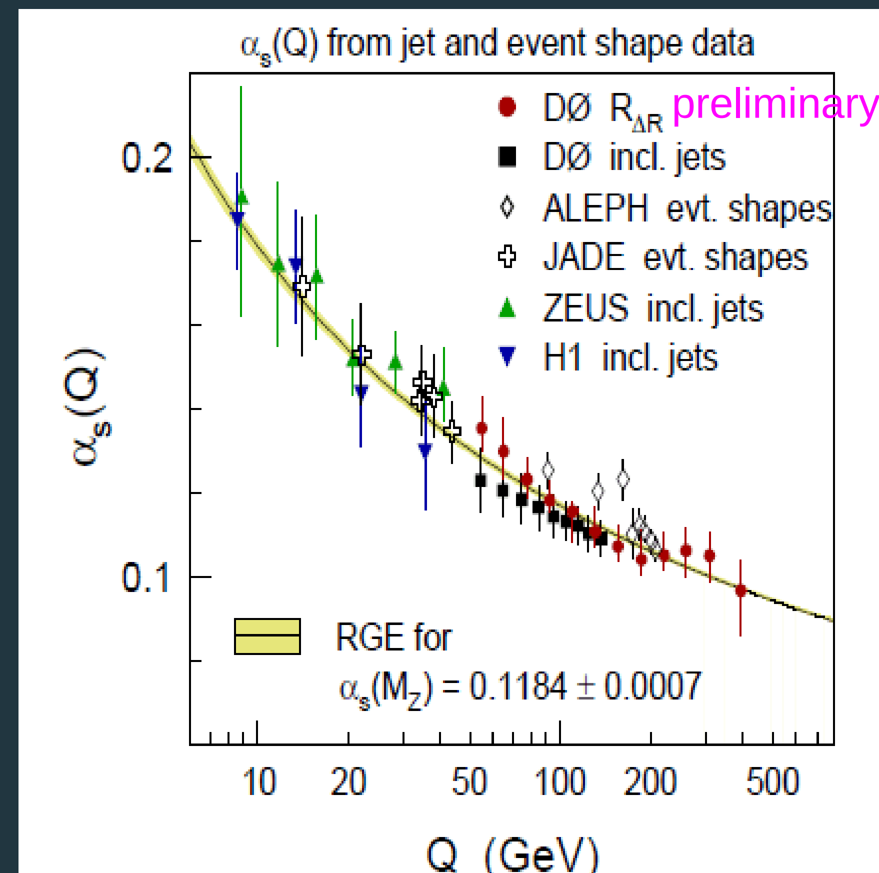
Benefits: systematic uncertainties mostly cancel out in the ratio (PDF uncert. <3%)



Analysis with $R_{\Delta R}$



Used to extract α_s



Using $R_{\Delta R}$ and NLO+MSTW2008NNLO PDFs

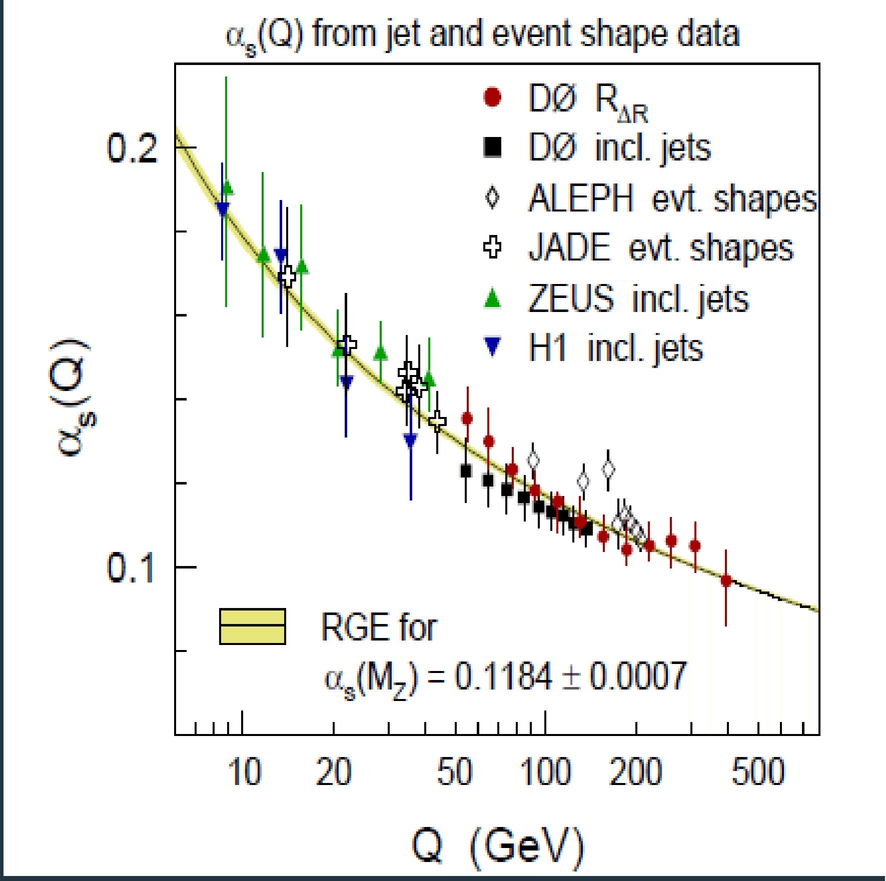
$$\alpha_s(M_z) = 0.1191^{+0.0048}_{-0.0071}$$

theory scale uncertainty dominates

Analysis with $R_{\Delta R}$

D0 Analysis	$\alpha_s(M_Z)$
$R_{\Delta R}$	$0.1191^{+0.0048}_{-0.0071}$
Inclusive Jets	$0.1161^{+0.0041}_{-0.0048}$

- → **$\alpha_s(p_T)$ results up to 400 GeV!**
- → $\alpha_s(p_T)$ decreases with p_T as predicted by the RGE
- → In agreement with ALEPH,JADE,ZEUS,H1 and world average $\alpha_s(M_z)$=0.1184±0.0007



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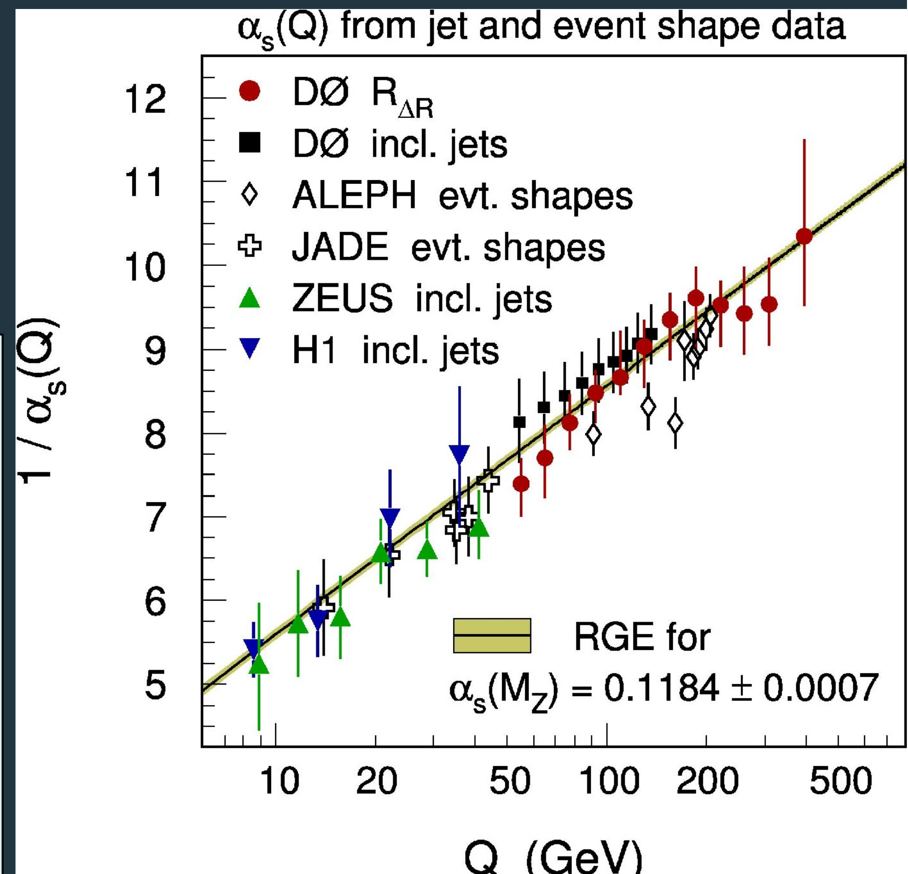
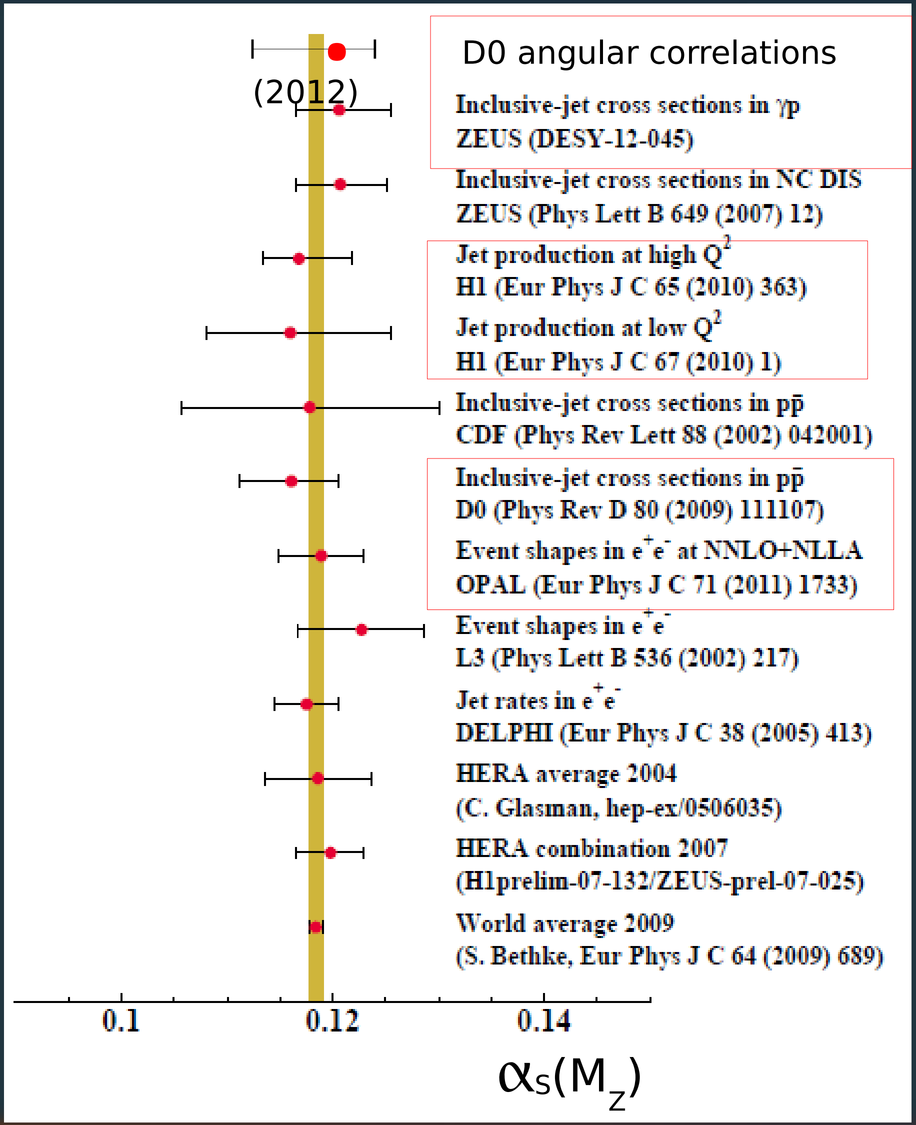


Compilation of α_S results (from jet data)

Active pursuits at Tevatron and LHC, particularly to push measures of $\alpha_s(p_T)$ to higher values



Results since 2009

Event Shapes

Geometric shape of the hadronic final state sensitive to details of QCD multijet production, but robust against experimental systematics, e.g. jet energy scale

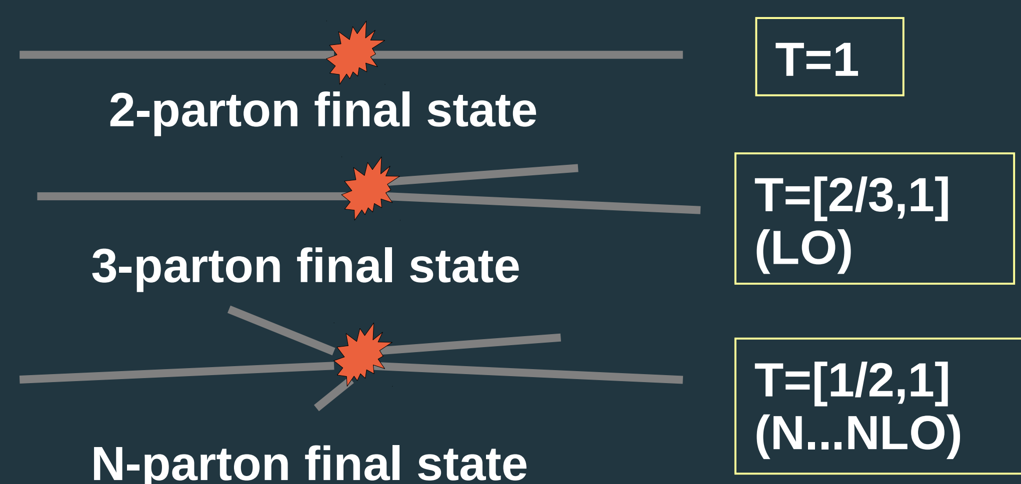
- Test of high order pQCD corrections
- Source of precise α_s (traditionally used in e+e-)

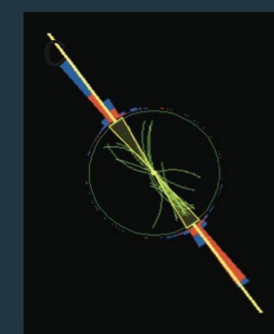
Example: Transverse thrust:

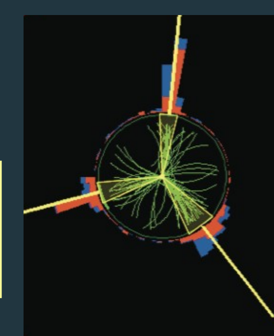
$$T = \max_{\hat{n}_T} \frac{\sum_i |\vec{p}_{T,i} \cdot \hat{n}_T|}{\sum_i |\vec{p}_{T,i}|}$$

$$\tau_{\perp} = 1 - T$$

$\hat{n}$: direction that maximizes T

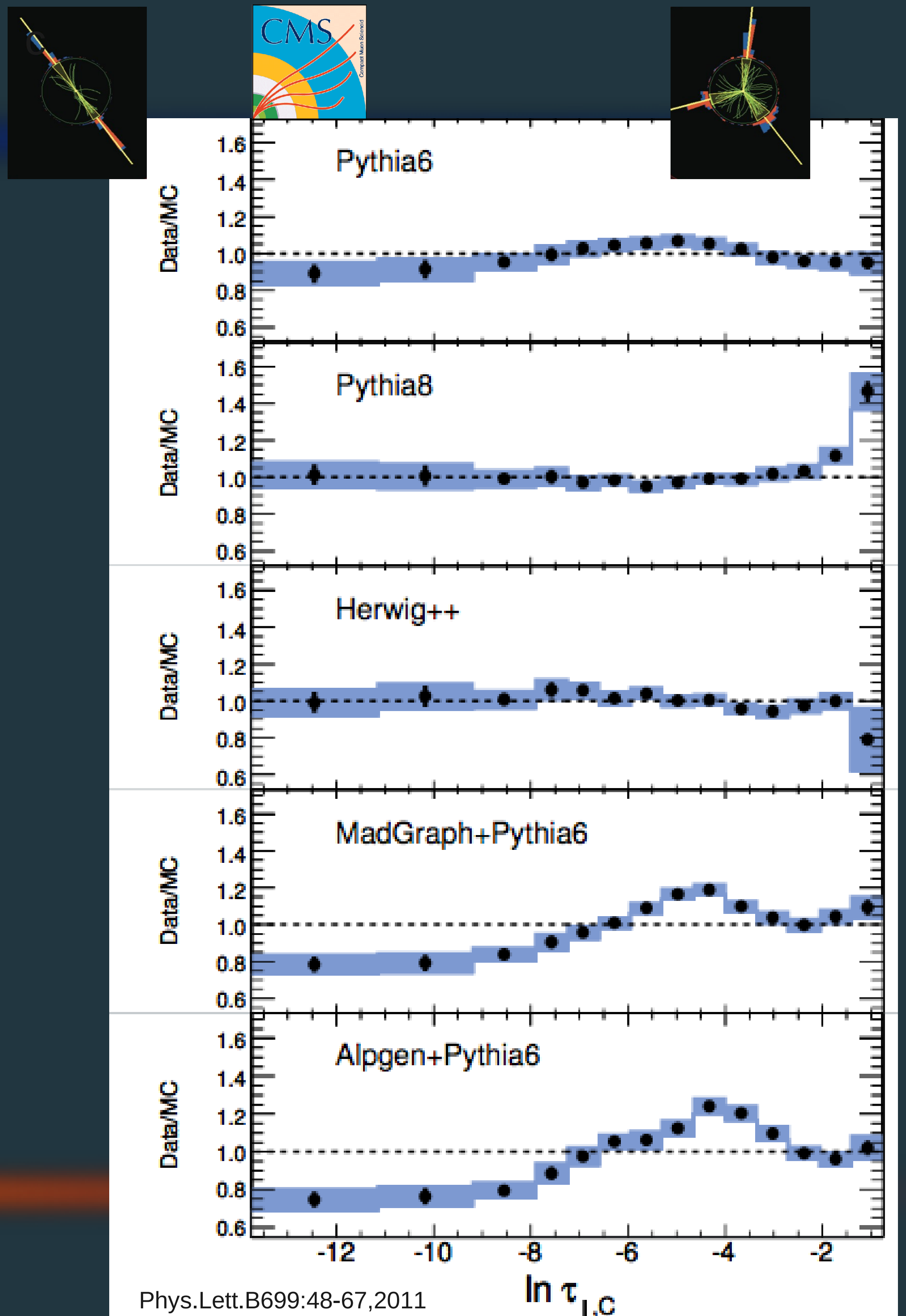






Event Shapes

CMS 2011 data



Phys.Lett.B699:48-67,2011

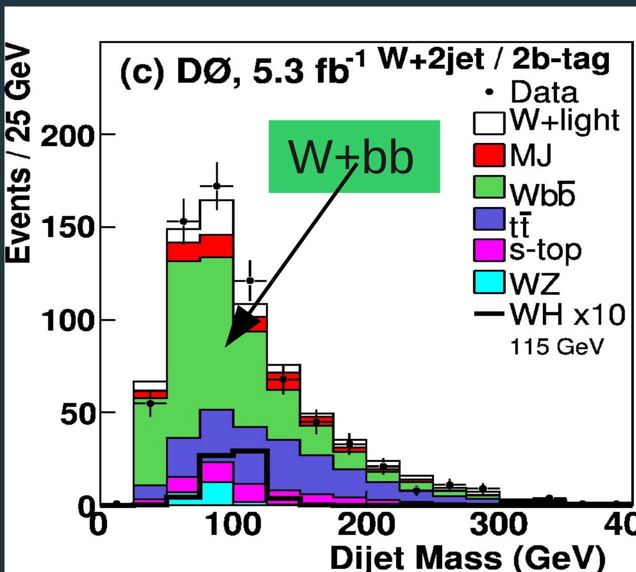
Pythia 6 (D6T), Pythia 8 (2C) and Herwig++ (2.3) agree with data, while MadGraph and Alpgen do not

Differential measures can be more sensitive to higher order effects than inclusive measures.

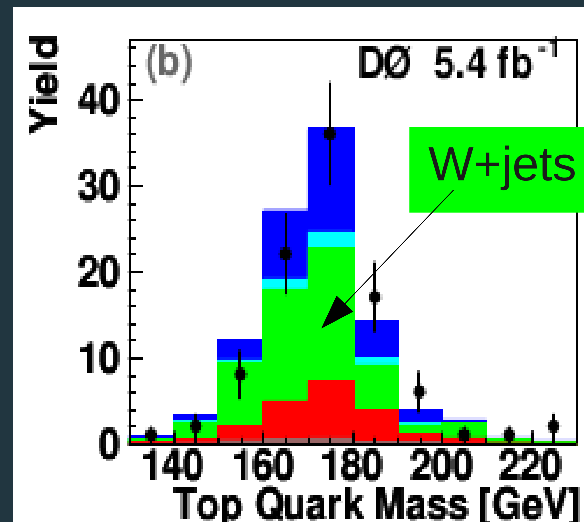
These kinds of studies provide input for improvements in current models of QCD multijet production.

V+jet production

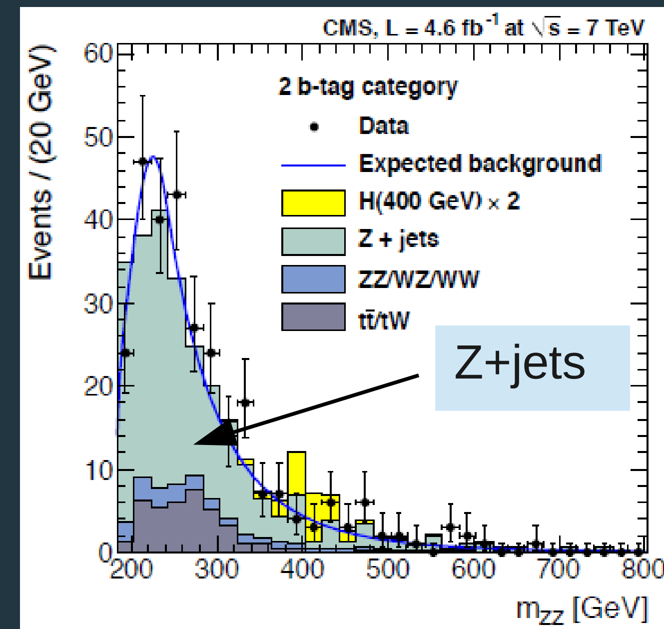
WH production



Single top production



H →ZZ→ 2l2q



Background to top-quark, Higgs, SUSY and other NP productions

Provide detailed measurements of p_T, system mass, and angular distributions of vector boson and jets

→ test of fixed order perturbative QCD (MCFM, Blackhat, Rocket, HEJ,..),
LO ME+PS predictions in MC event generators (Alpgen,Sherpa,Madgraph,..)

→ testing and tuning of phenomenological models

→ All experiments are heavily involved in such tests

W+jets

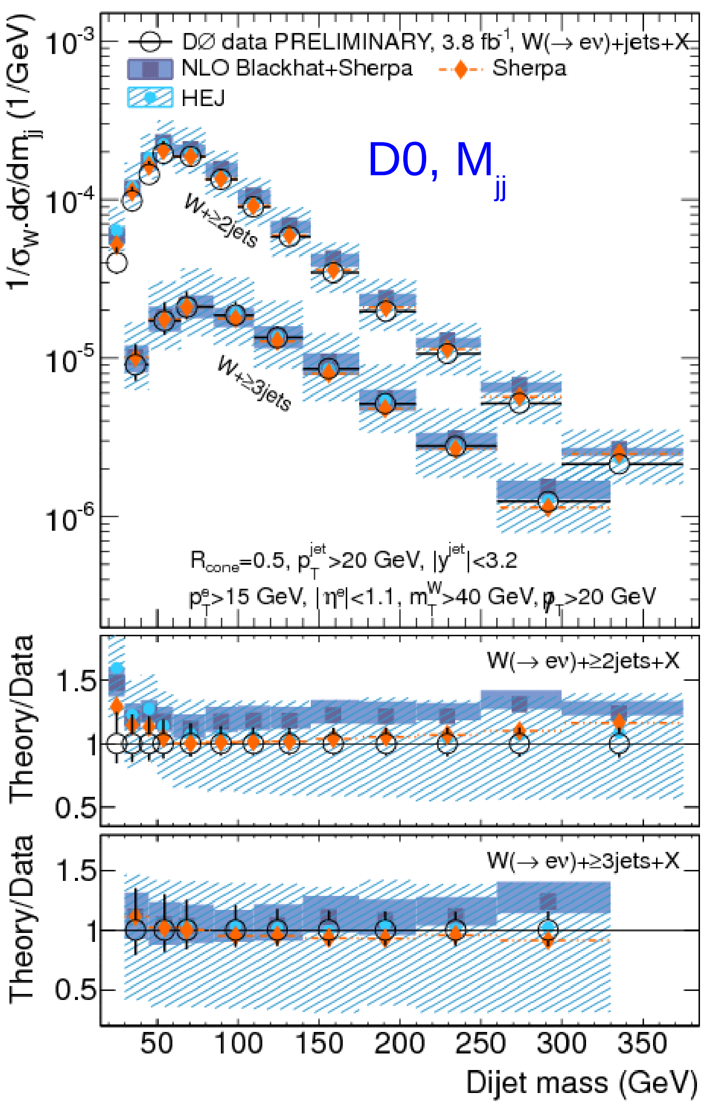
Dominant background to ttbar production, Higgs boson, many non-SM processes

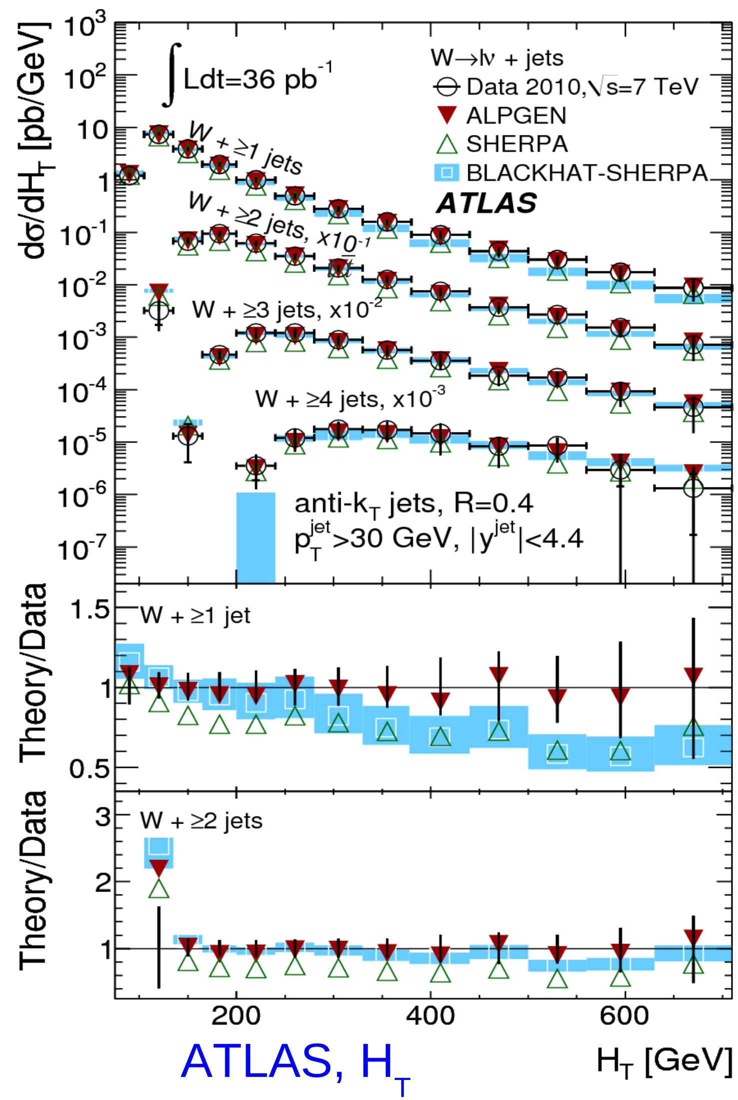
=> extensively studied in all Tevatron and LHC experiments:

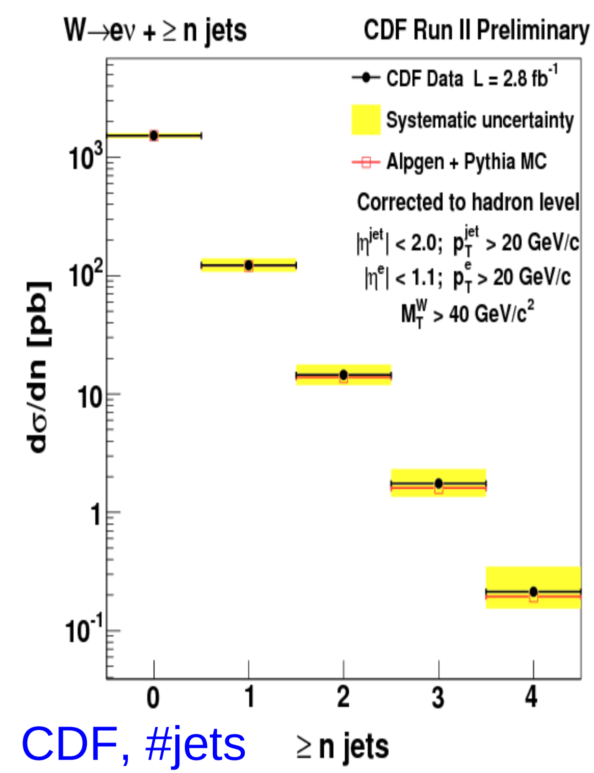
jet p_T, H_T, #jets, jet angular, masses, 3rd jet emission prob, etc.

Good agreement with NLO (Blackhat+Sherpa, HEJ) for most of phase space

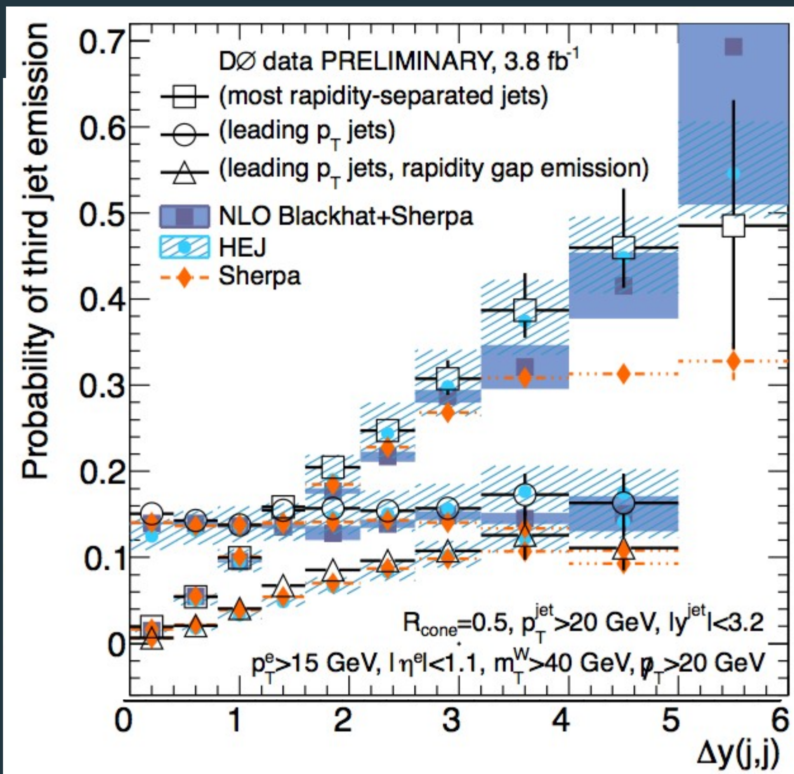
(Blackhat: some tension for W+2jet in $M_{jj,}$ and high H_T)







W+jets: jet emission



Examine probability of third jet emission in inclusive W+dijet events, as a function of dijet rapidity separation(s).

1) *Δy* (leading jets)
2) *Δy* (leading jets w/ emission in rapidity gap)
3) *Δy*, (most forward/backward jets)

Notable differences in jet emission into the rapidity gap for p_T and rapidity ordered jets

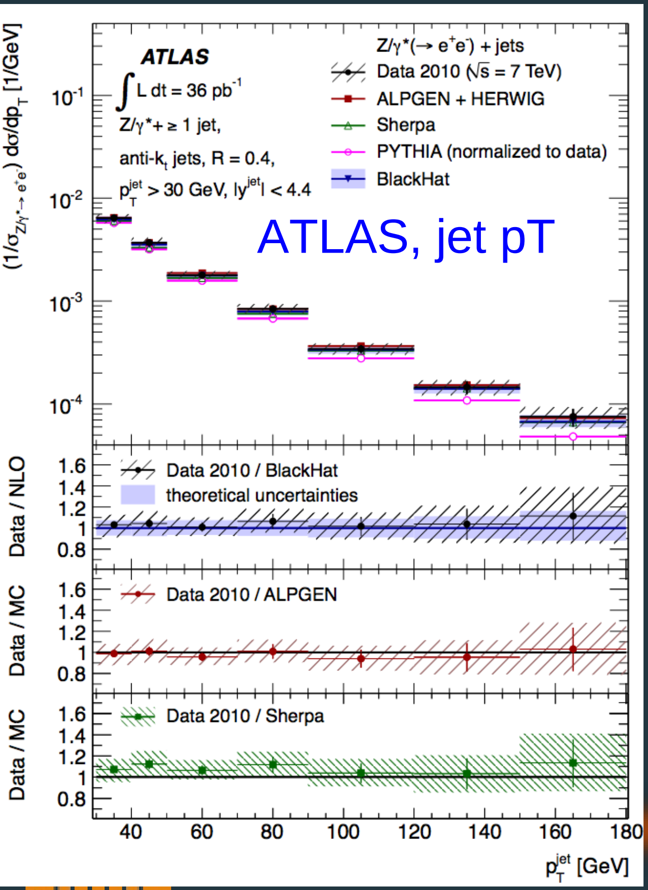
First results of their kind for V+jet precesses => unique inputs for event generator models (also >40 other distributions under study!)

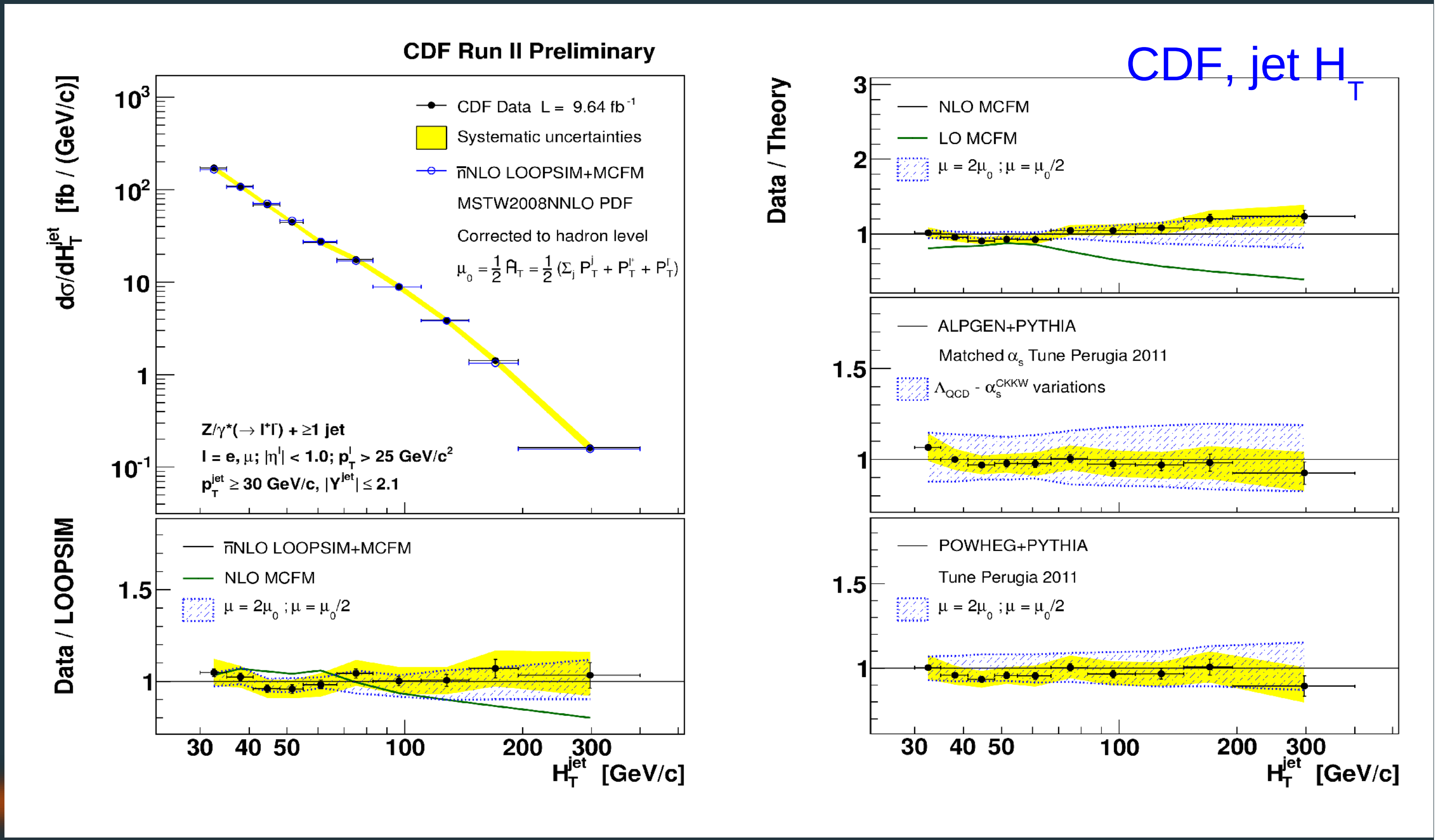
Data can be reinterpreted as a measure of the gap fraction (with a jet veto scale of 20 GeV), relevant for processes like Vector Boson Fusion

Z+jets

Detailed studies on Z(ll)+jet production coming out vs jet p_T, N_{jets}, H_T, etc

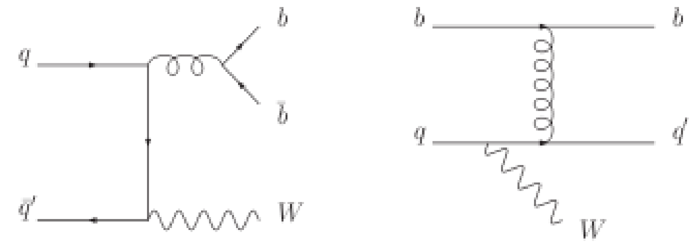
- comparisons with state-of-the-art theory calculations
- good agreement with NLO pQCD (BlackHat and MCFM)
- LO ME+PS (Alpgen), NLO+PS (Powheg) properly model data with large scale uncertainty
- Good modeling with approximate nNLO LOOPSIM with reduced scale uncertainty





W+b

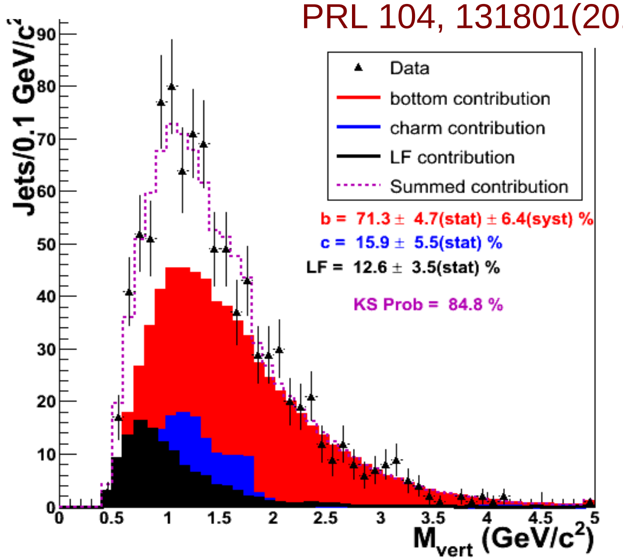
- Tests of pQCD
- Very important background to SUSY and Higgs boson searches
- Measured total *exclusive* W+b cross sections, up to two jets in the final state with jet pT>20 (25) GeV and |y|<2.0 (2.1) at CDF (Atlas)



~90% (50%)@ TeV(LHC)

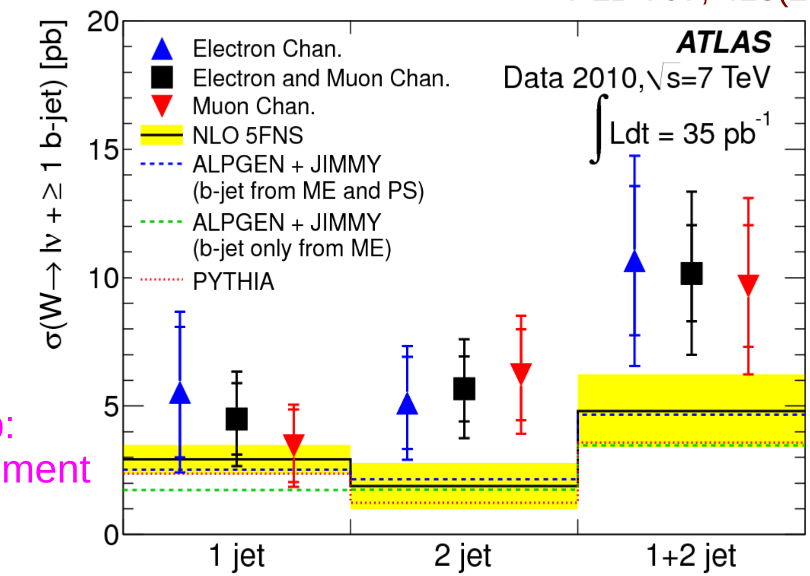
CDF

PRL 104, 131801(2010)



ATLAS

PLB 707, 418(2012)



W+1b: agreement

σ(W+b-jets) · BR(W → lν) [pb]:

Data: $2.74 \pm 0.27(stat) \pm 0.42(syst)$

NLO : 1.20 ± 0.14

$10.2 \pm 1.9(stat) \pm 1.6(syst)$

$4.8^{+1.2}_{-0.7}(scale)^{+0.3}_{-0.0}(PDF)^{+0.3}_{-0.2}(m_b) \pm 0.3(np.corr)$

Data/NLO **about factor 2**

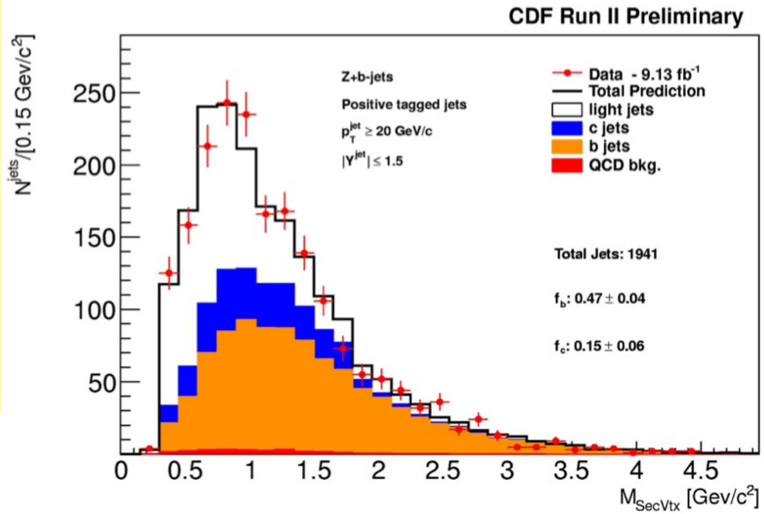
Difference: ~3σ ~1.5σ

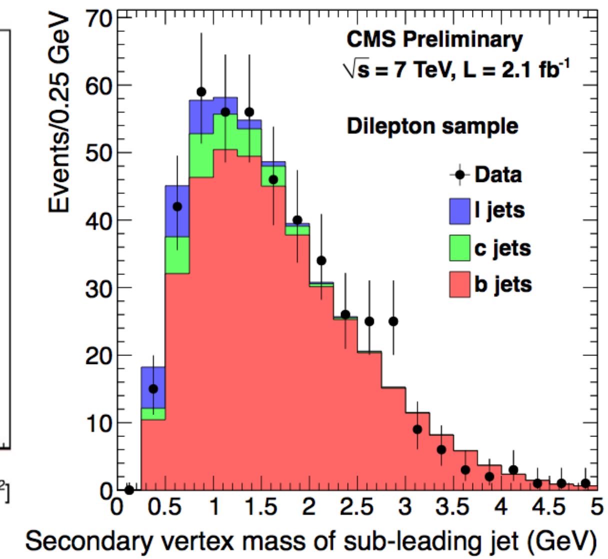
=> Should be cross-checked in at at least one more measurement, preferably *inclusive* *and differential*

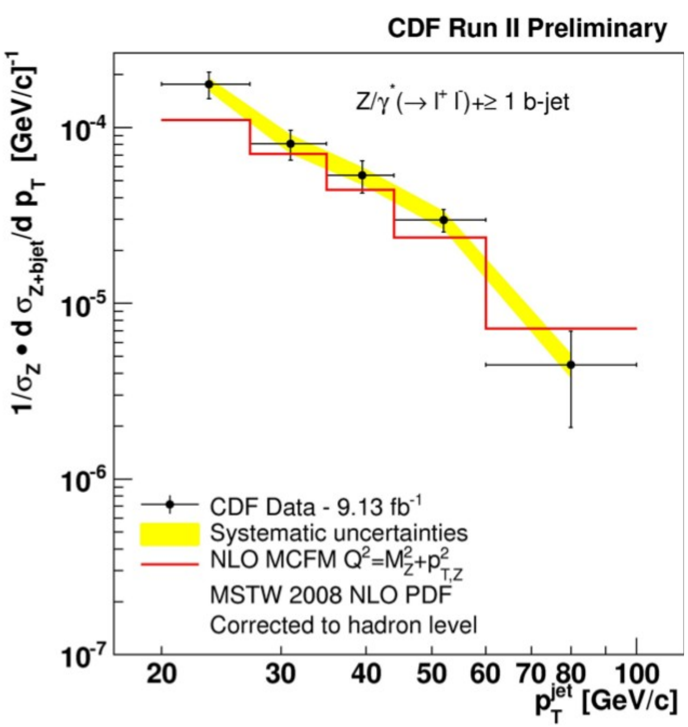
Z+b

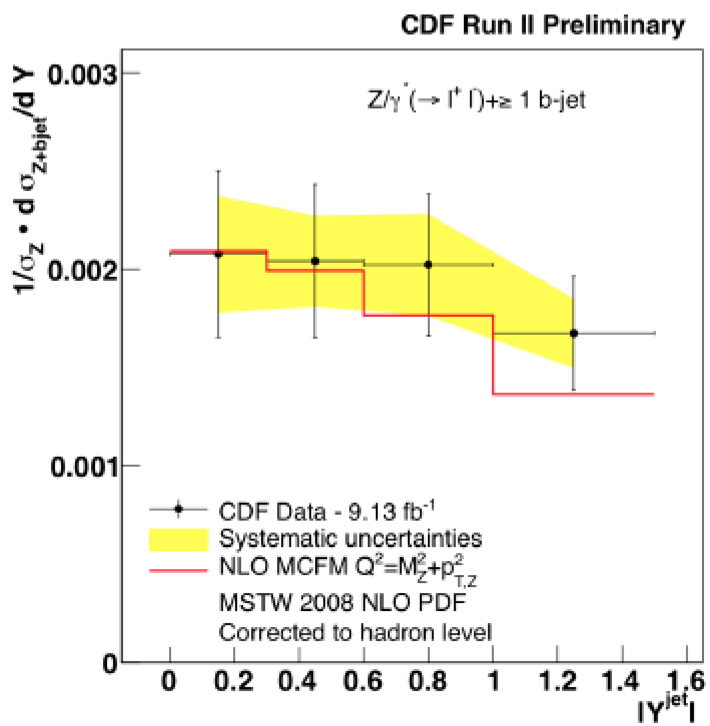
- Z+bb important background for single top, ZH, new phenomena
  - measure ratio with respect to inclusive Z and Z+jet
- Studies of Z+b and Z+bb find good agreement with NLO predictions (20-25% uncert.) in all experiments

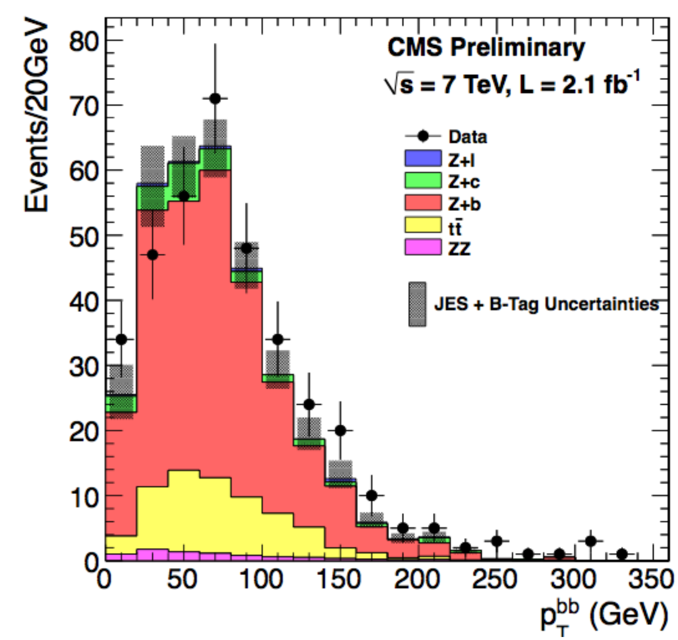
Good modeling of secondary vertex mass





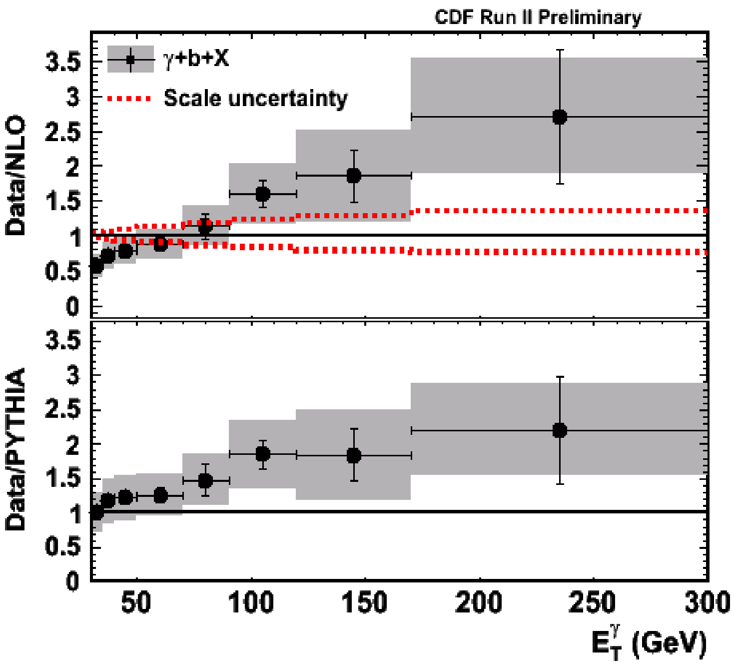


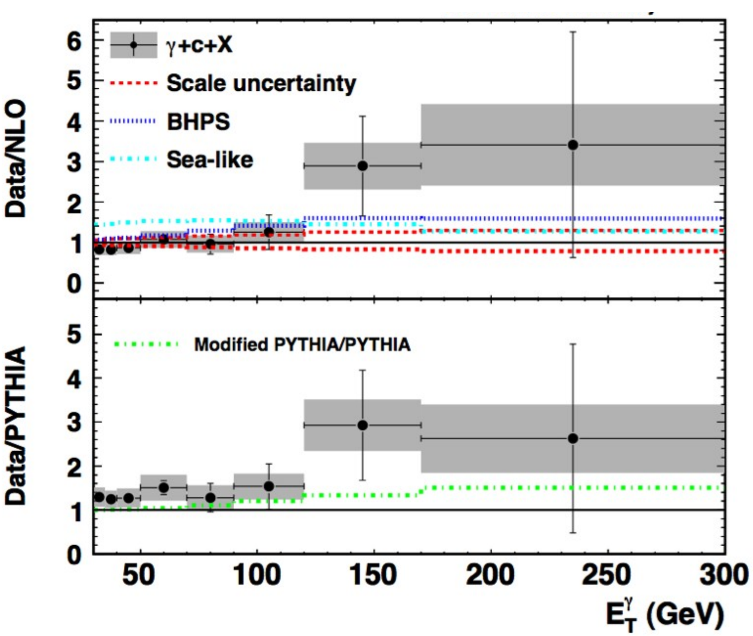




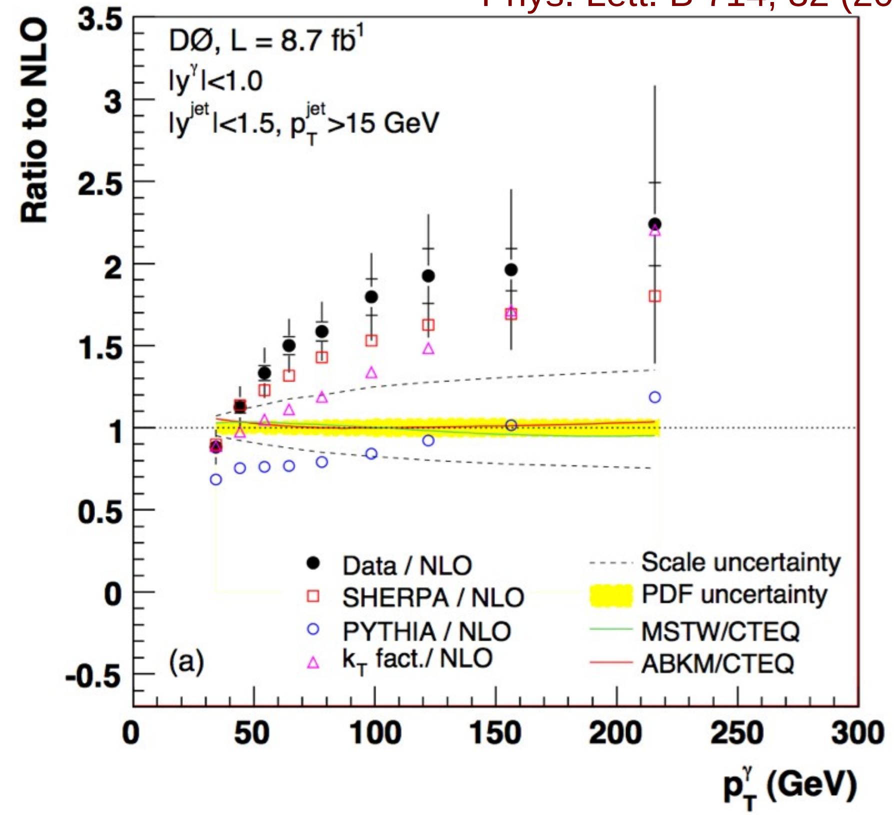
Photon+HF jets

- Photon+heavy flavor jet measurements
- photon+b/c in CDF, photon+b in D0
- in agreement with NLO predictions only up to $p_T \sim 70$ GeV
  - D0 and CDF agree at $p_T > 70$ GeV
  - good description of data requires higher order corrections present



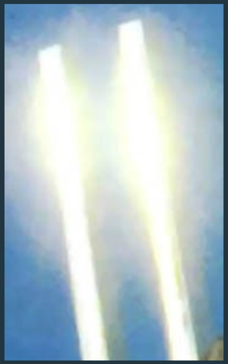


Phys. Lett. B 714, 32 (2012)



Tevatron: $q\bar{q} \to \gamma g\,(g \to b\bar{b})$ dominates at pT>80 GeV
LHC: $bg \to b\gamma$ dominates at most pT
=> similar measurement at LHC is needed

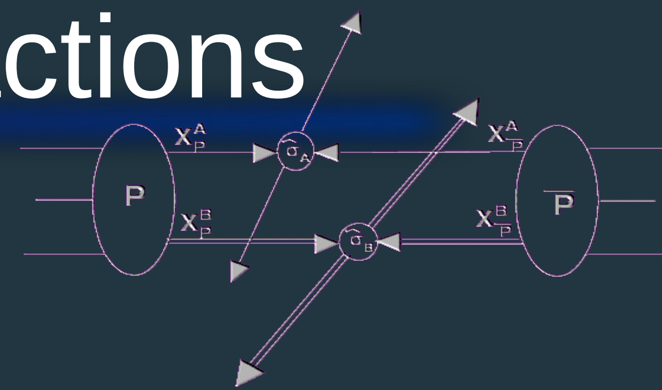
Many areas of complimentary



Many areas of complimentary

(talk by E. Dobson)

Double parton interactions



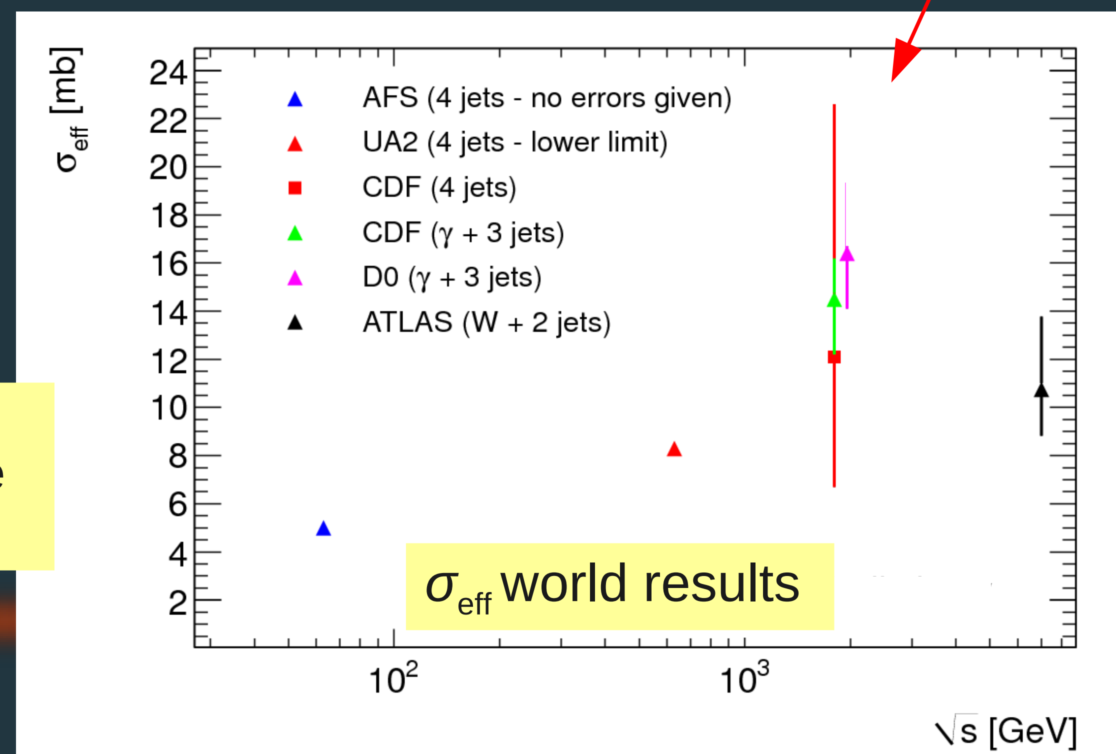
Study of events with double parton scattering at high p_T regime using jet final states

=> Each parton process is hard/pert. calculable

Complementary information about proton structure:

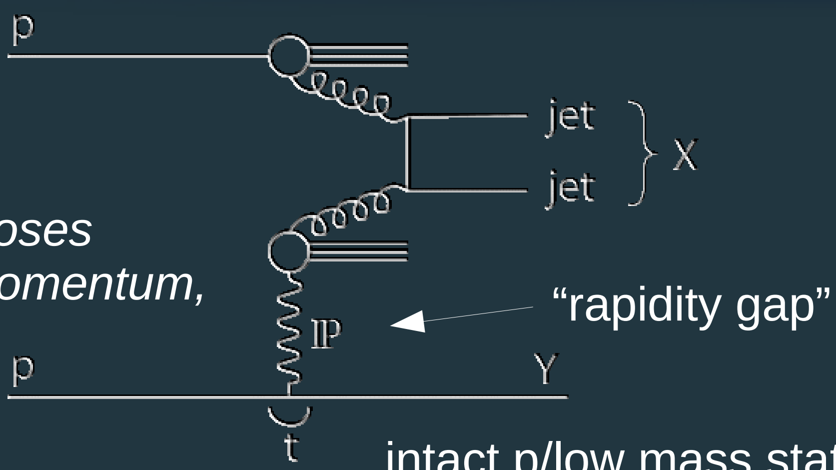
- Spatial distribution of partons, impact on PDFs
- Needed for understanding multijet signal events and correct background estimates for rare processes.

$\sigma_{DP} = \sigma_A \sigma_B / \sigma_{eff}$



More measurements are needed to check E and flavor dependence of σ_{eff}

Jets in hard diffraction

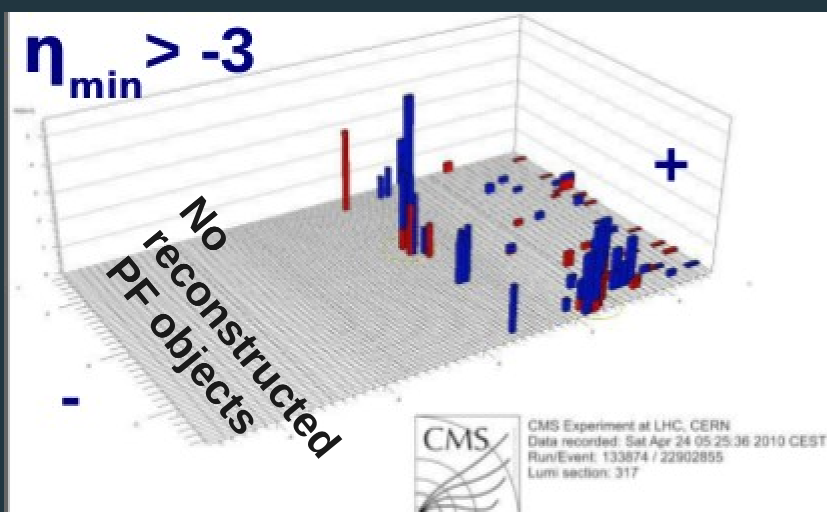


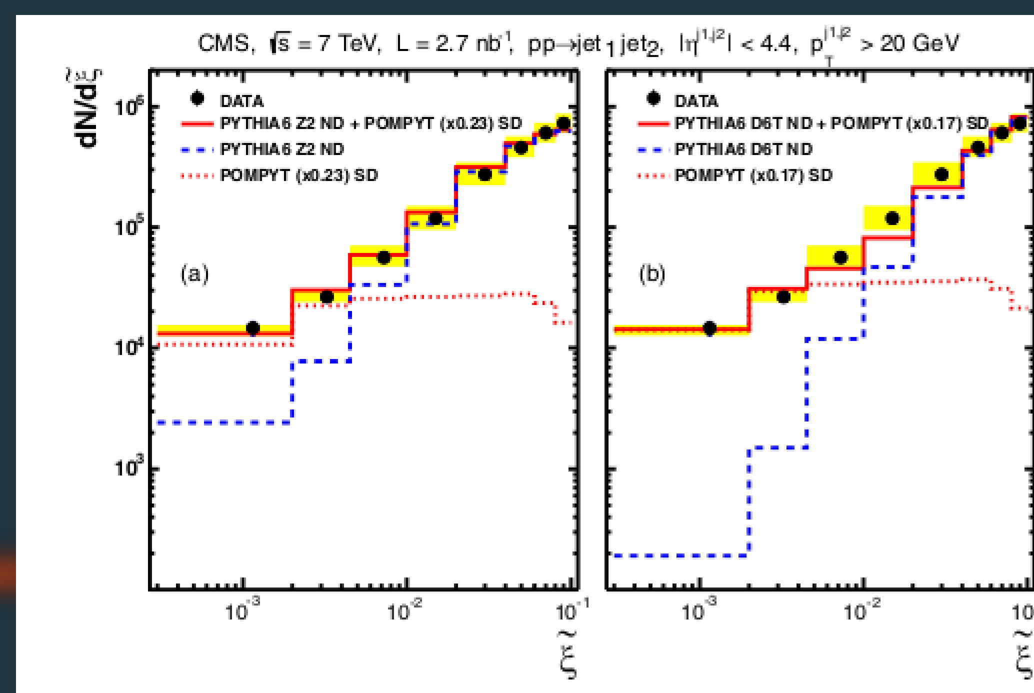
looses momentum, ξ

intact p/low mass state

Significant fraction of the total inelastic pp cross section at high energies is attributed to diffractive processes

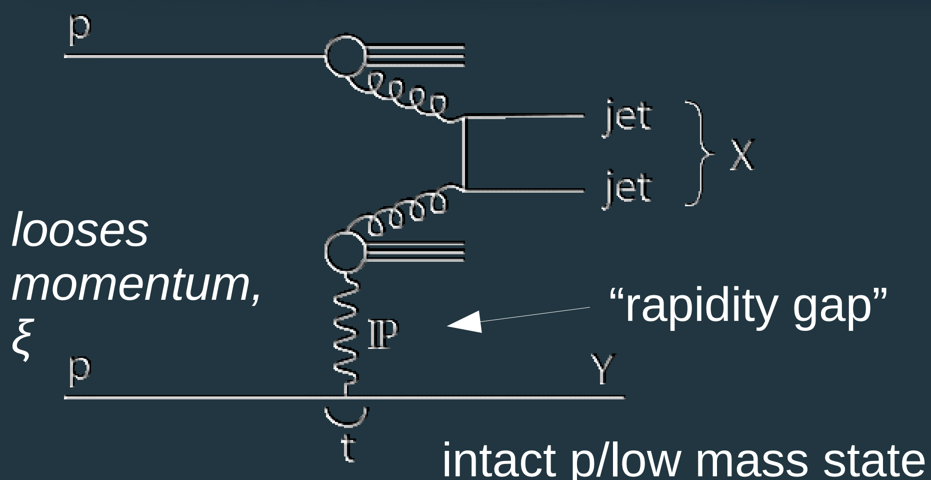
characterized by the presence of a large rapidity region Δy with no hadrons, usually called "rapidity gap"





Submitted to PRD

Jets in hard diffraction



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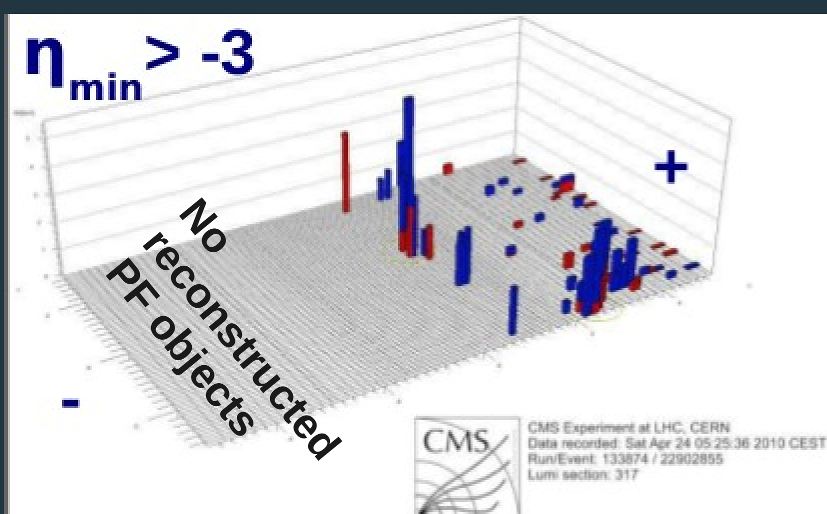

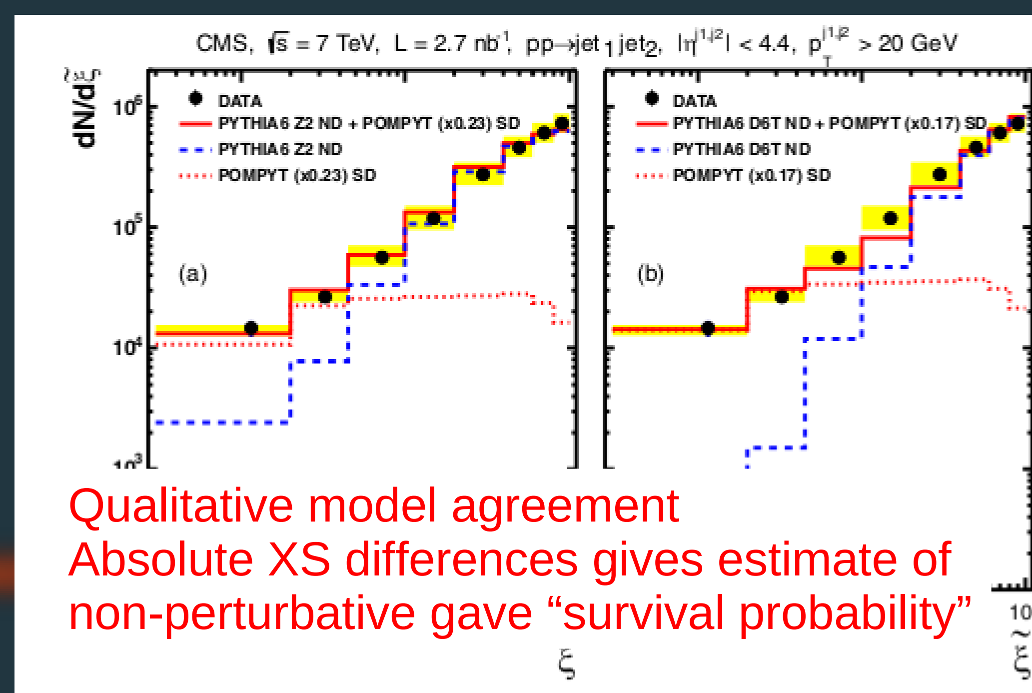

Qualitative model agreement
Absolute XS differences gives estimate of non-perturbative gave “survival probability”

Submitted to PRD

Summary

- Good consistency/complementarity for most of experimental data

- Precise handles on experimental uncertainties <= theoretical uncertainties

- Jet results yield precision measurement of fundamental observables
  - sensitivity to PDF sets, strongest constraint on gluon PDF
  - extraction of αs and test of its running up to 400 GeV
  - important contributions to limits on many NP models

- W/Z/γ+jets results => extensive tests of pQCD and MC models; in many cases, a triumph of NLO and ME-PS MC predictions. Wealth of tuning data!

- Improving phenomenological models with double parton and diffractive events

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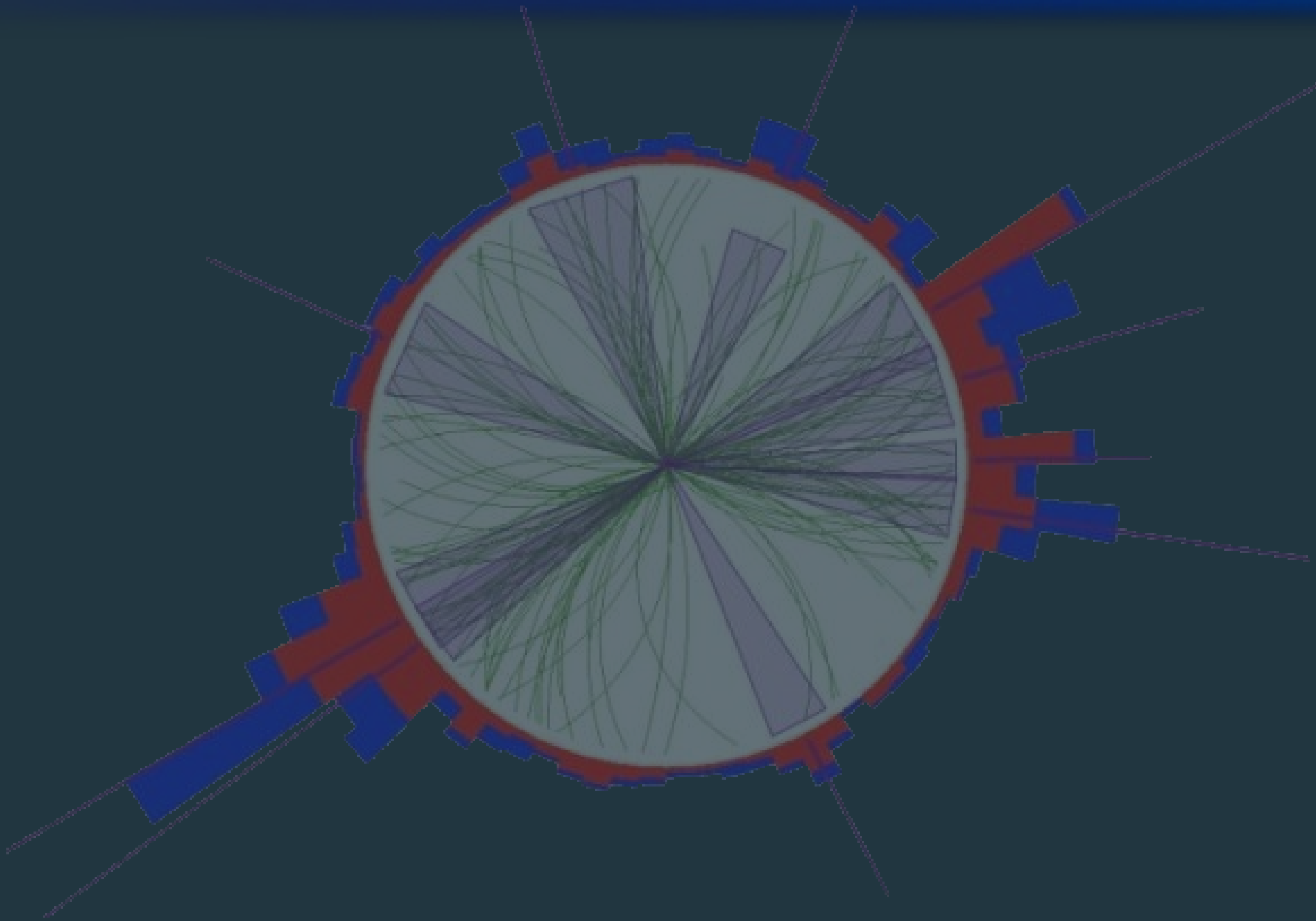
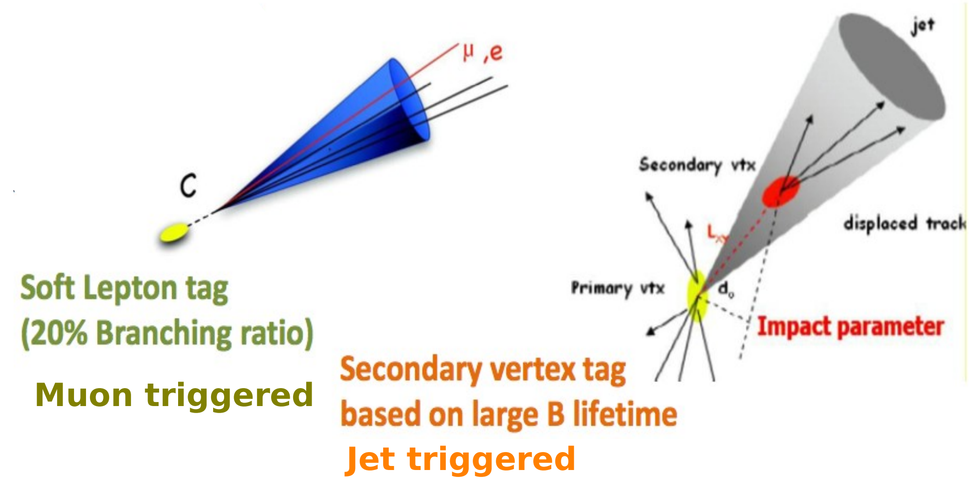
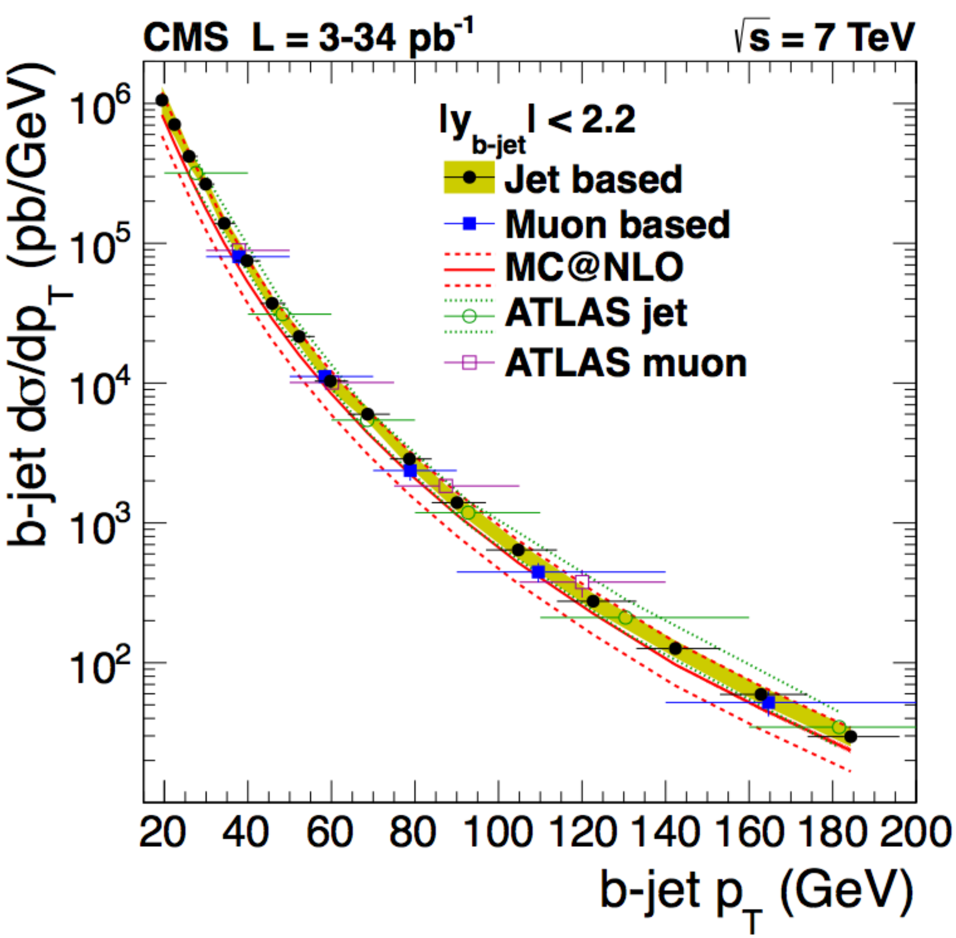
Additional slides

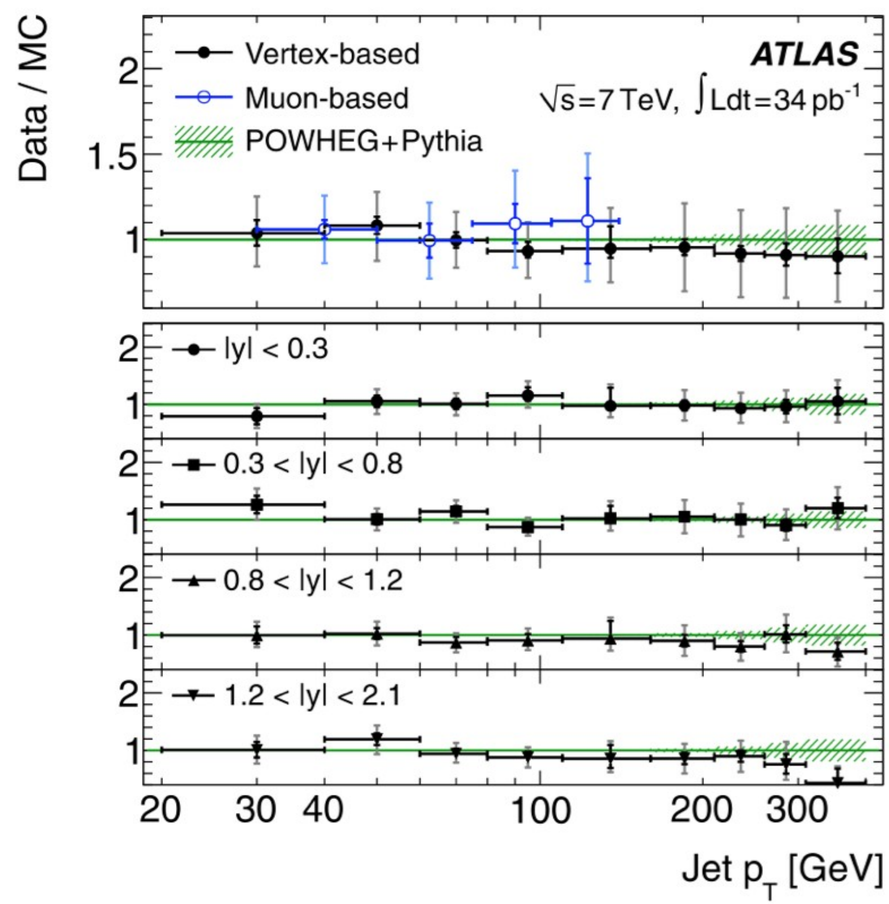


Inclusive b-jets

- B-jet cross section 2-4% of inclusive jets
- Inclusive b-jet cross sections at ATLAS and CMS agree with Powheg
  - data bit higher than MC@NLO predictions
  - gluon-splitting large contribution at LHC at low pt



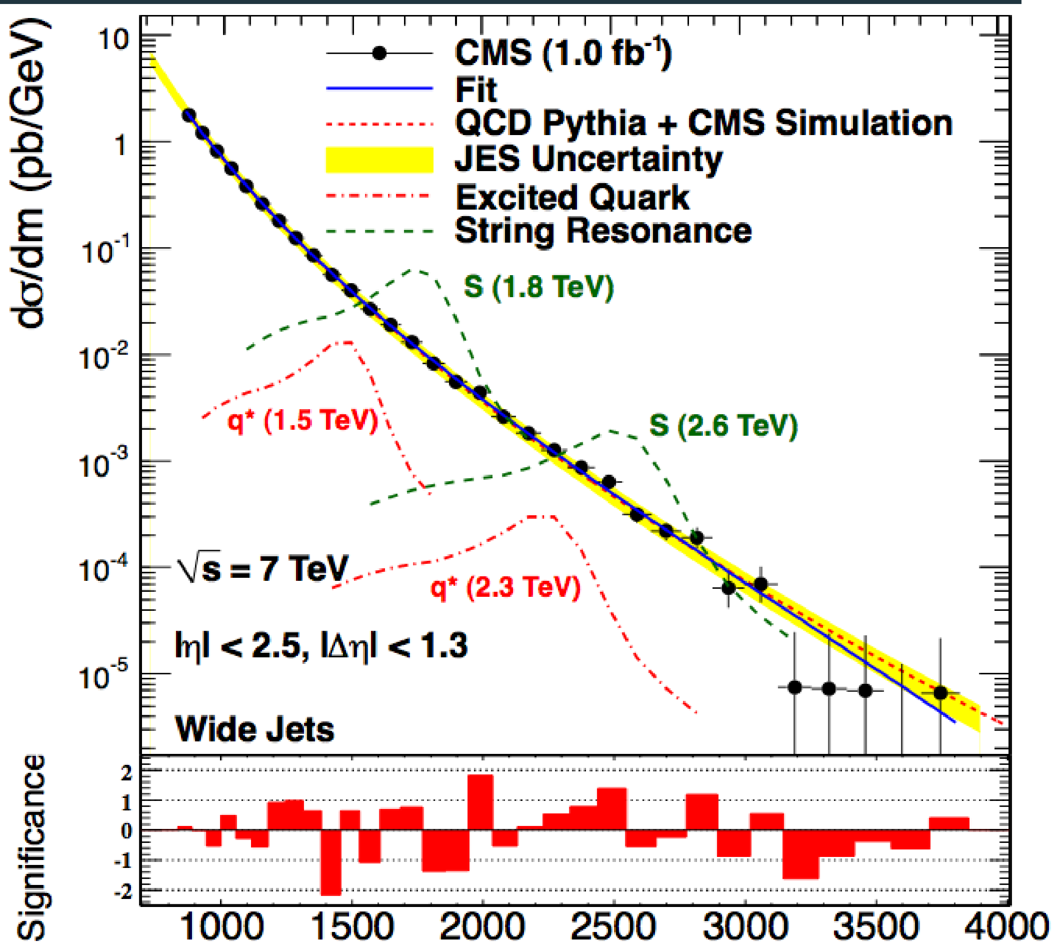




Bump hunts

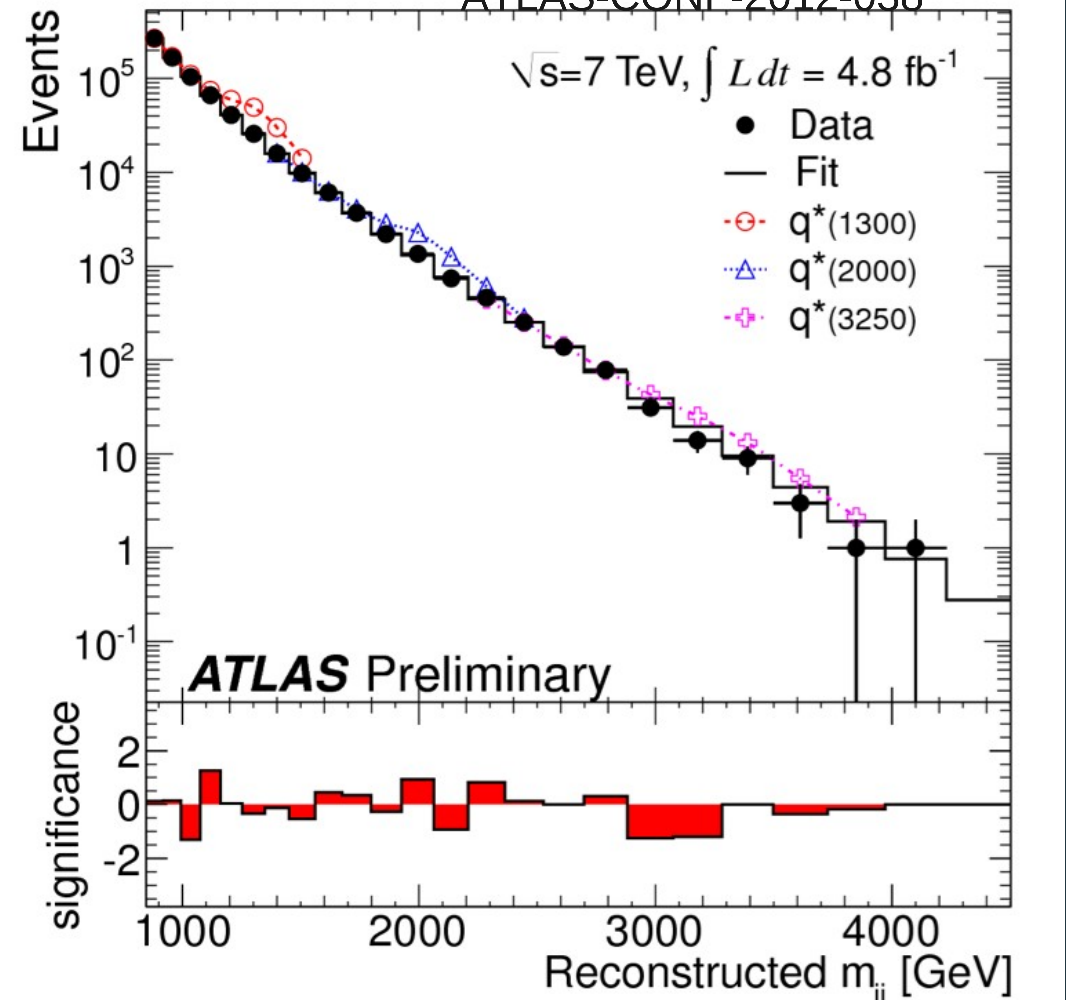
LHC 7 TeV data

So far no new resonances observed up to several TeV



CERN-PH-EP-2011-119

ATLAS-CONF-2012-038



W+Jets

W+(n)jets differential cross-sections measured as a function of P_T^W, $y(n^{th}\ jet)$, M_{dijet}, $\Delta y(j,j)$ for inclusive one to four jet events

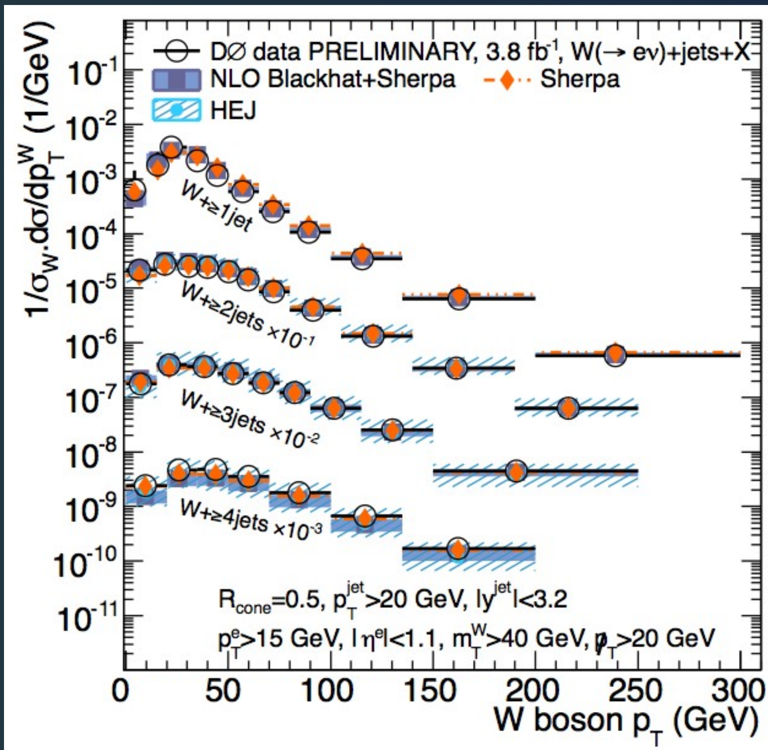
- All distributions unfolded to particle-level for comparison to theoretical predictions using Singular Value Decomposition technique (Guru)
  - Proper handling of bin migrations
  - Reduced Monte Carlo dependence

Comparisons made to three theory predictions:

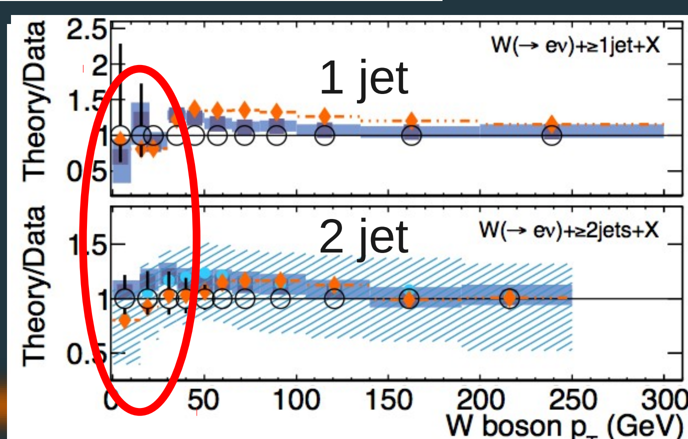
- Sherpa (MEPS event generator)
- NLO Blackhat+Sherpa
- High Energy Jets (HEJ – all-order resummation)

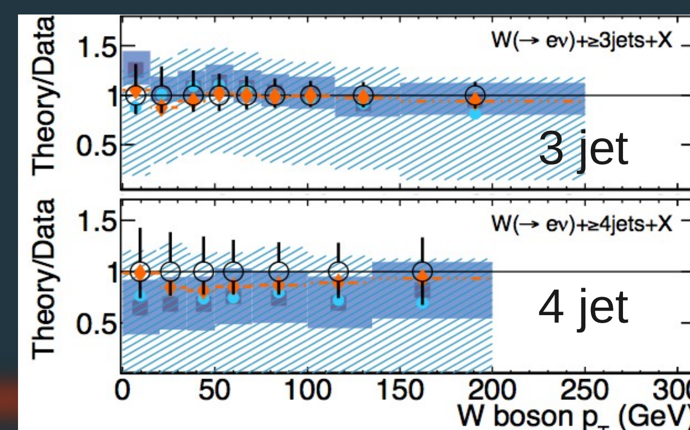
Comprehensive program of study involving 40 variables in full

P_T^W

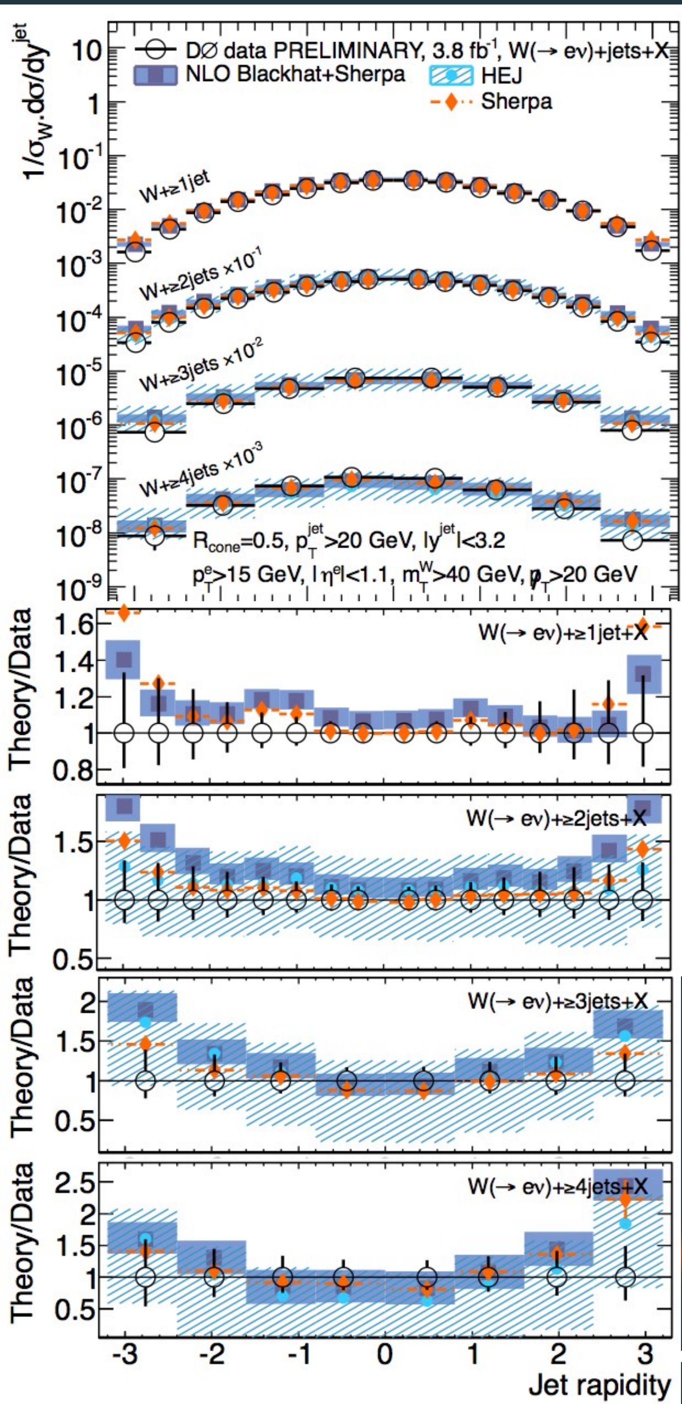


- All approaches show good agreement on this basic observable
- Some breakdown where non-perturbative corrections to P_T^W become large ≈ jet p_T threshold (20 GeV)
- Uncertainties on data smaller or equal in magnitude to uncertainties on theory predictions





W+jets rapidities



W+(n)jets differential cross-section measured as a function of nth jet rapidity in inclusive n-jet events (for n=1—4)

Good agreement between data and theory at central rapidities, with small uncertainties

Theory predictions tend to overestimate cross-section in forward region: dominated by low p_T jets

Many analyses are sensitive to discrepancies in jet rapidity modelling