Jet Physics

Kenichi Hatakeyama

畠山　賢一

Baylor University

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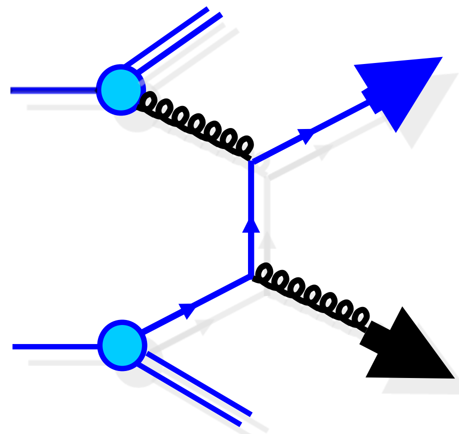
Yesterday's Summary

- Jets play important roles in various aspects of particle physics
  - QCD studies: quark/gluon properties, QCD SU(3) structure, α_s, PDF, etc
  - And searches for Higgs and physics beyond the Standard Model
    - As a signal or as a background source
- After many years of work, jet algorithms are quite established now
  - Infrared and collinear safe algorithms are available that work well for both experimentalists and theorists
  - Features of each algorithm is now well understood
- Jet energy calibration takes a lot of effort
  - The experience from the Tevatron greatly benefits LHC experiments
- Inclusive jet production at HERA (and Tevatron)
  - Provide important information for α_s and PDF

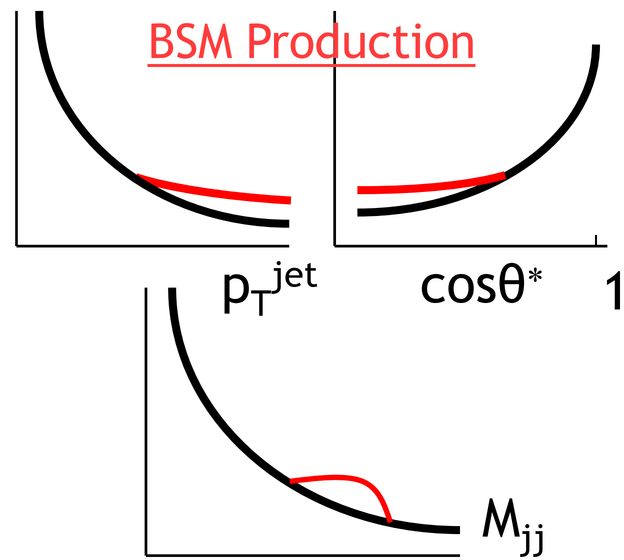
Inclusive Jet Production in pp($p\bar{p}$)



QCD Production

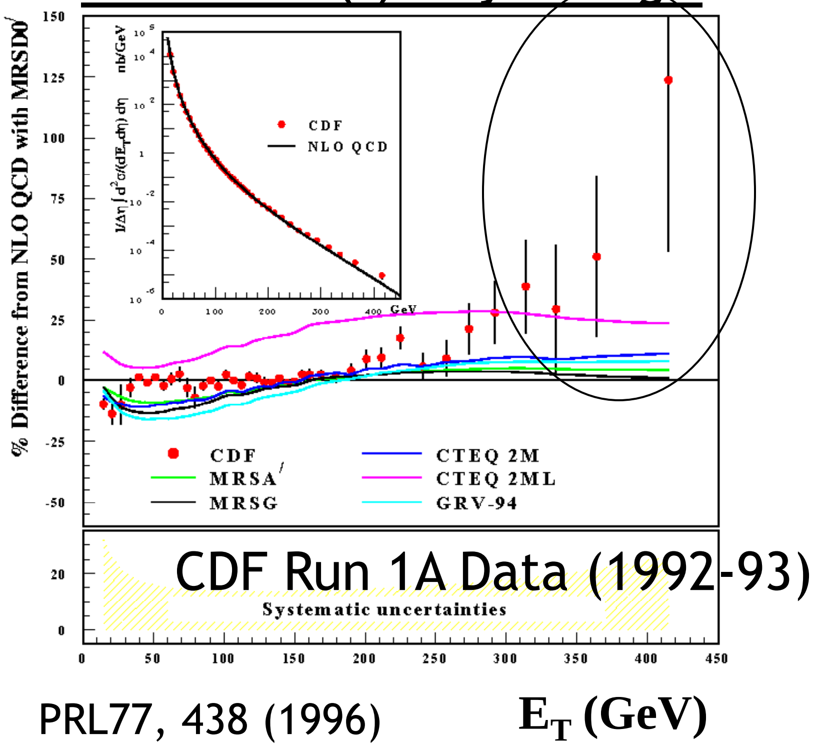
$$\sigma_{jet} = \sum_a \sum_b f_{a/p}(x_p, \mu_F^2)\, f_{b/\bar{p}}(x_{\bar{p}}, \mu_F^2)\, \hat{\sigma}_{a,b}\left(p_p, p_{\bar{p}}, \alpha_s(\mu_R^2), \frac{Q^2}{\mu_F^2}, \frac{Q^2}{\mu_R^2}\right)$$

- Test pQCD at highest Q^2.
- Unique sensitivity to new physics
  - Compositeness, new massive particles, extra dimensions, …
- Constrain PDFs (especially high-gluons)
- Measure α_s

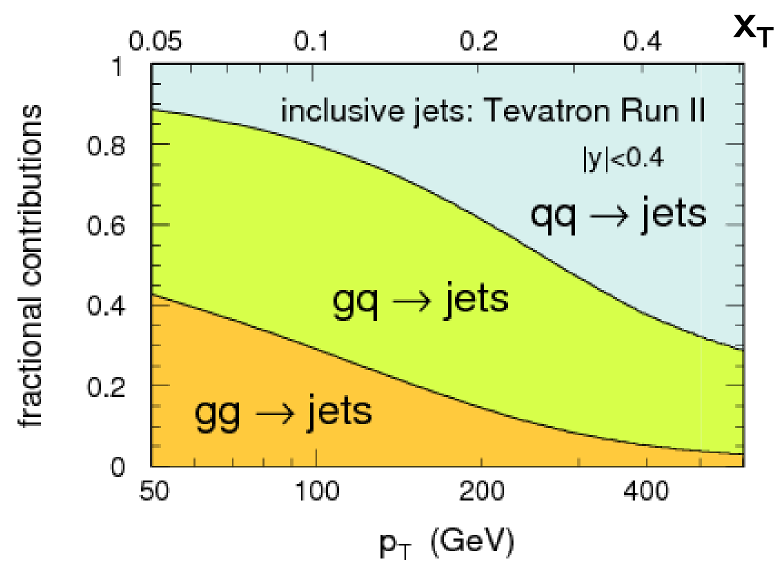


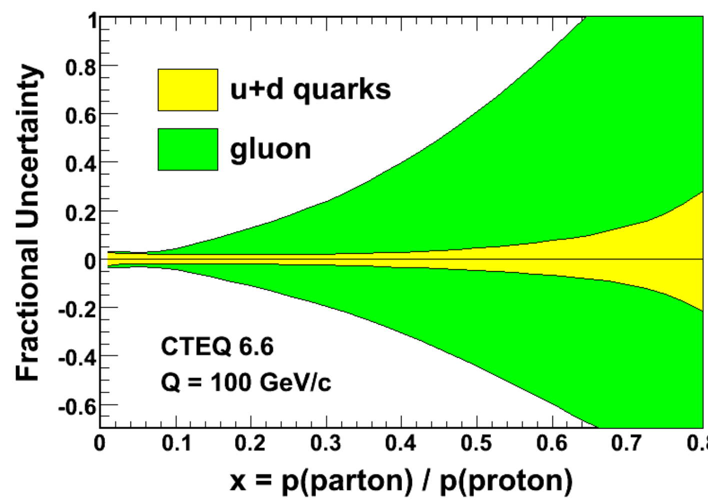
A Little History

Excitement(?) 15 years ago



PRL77, 438 (1996)



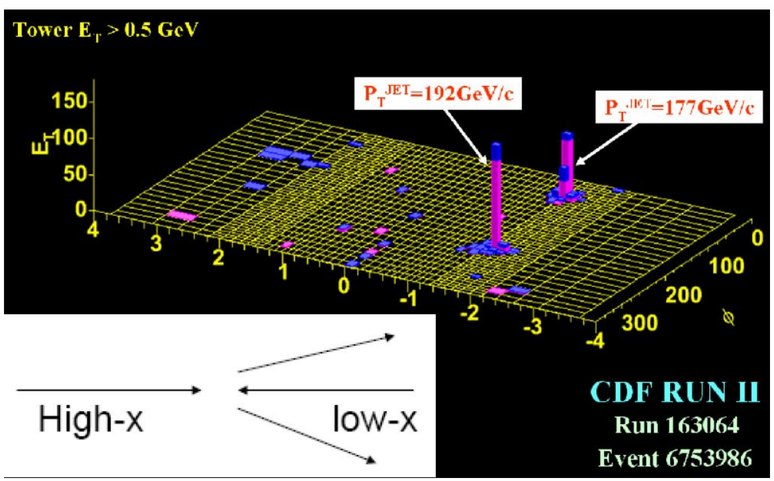


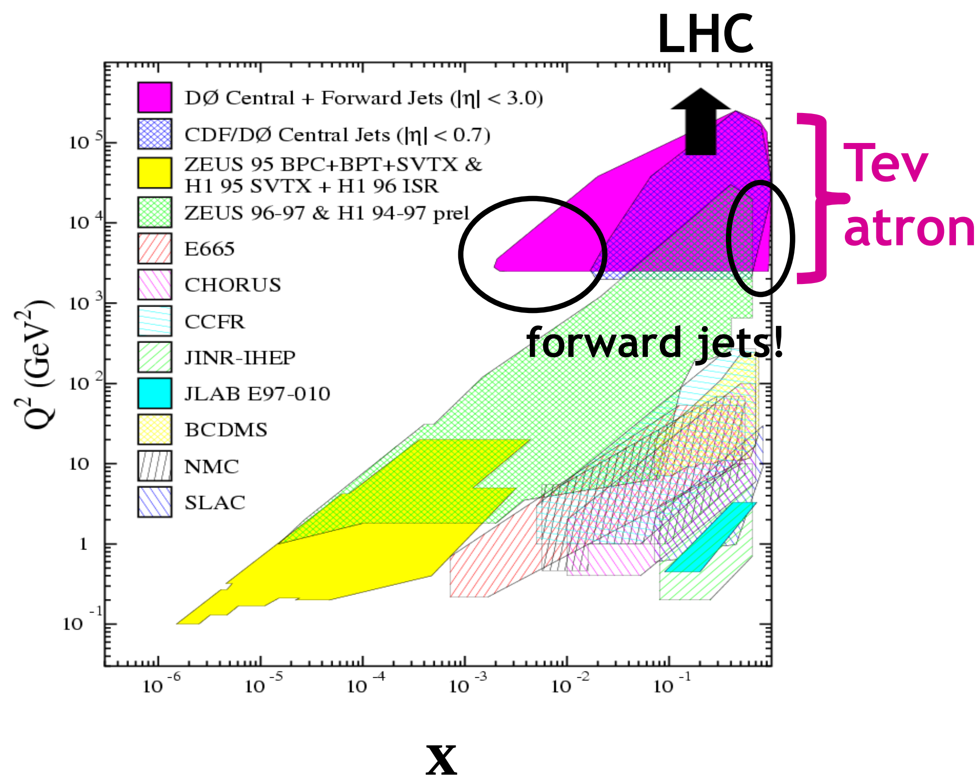
High-x gluon not well known

...can be accommodated
in the Standard Model

Forward (High |y|) Jets

- Forward jets probe high-x at lower Q^2 (= $-q^2$) than central jets
  - Q^2 evolution given by DGLAP
  - Essential to distinguish PDF and possible new physics at higher Q^2
- Also, extend the sensitivity to lower x





Inclusive Jet Cross Section Measurement

- How do we measure?

$$\frac{d^2\sigma}{dp_T dy} \leftrightarrow \frac{\boxed{N_{jet}}}{\boxed{\Delta p_T \cdot \Delta y} \cdot \boxed{\varepsilon} \cdot \boxed{\int Ldt}} \cdot \boxed{C_{unfolding}} \; vs. \; \boxed{jet\ p_T}$$

# of jets in each (Pt, y) bin

Jet energy calibration

Pt and y bin width

Event/jet selection efficiency

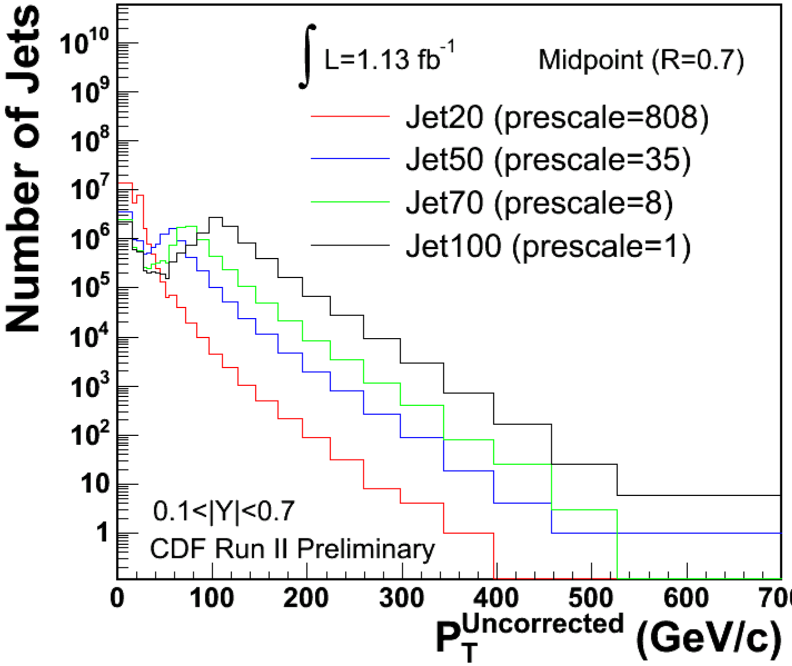
Integrated luminosity

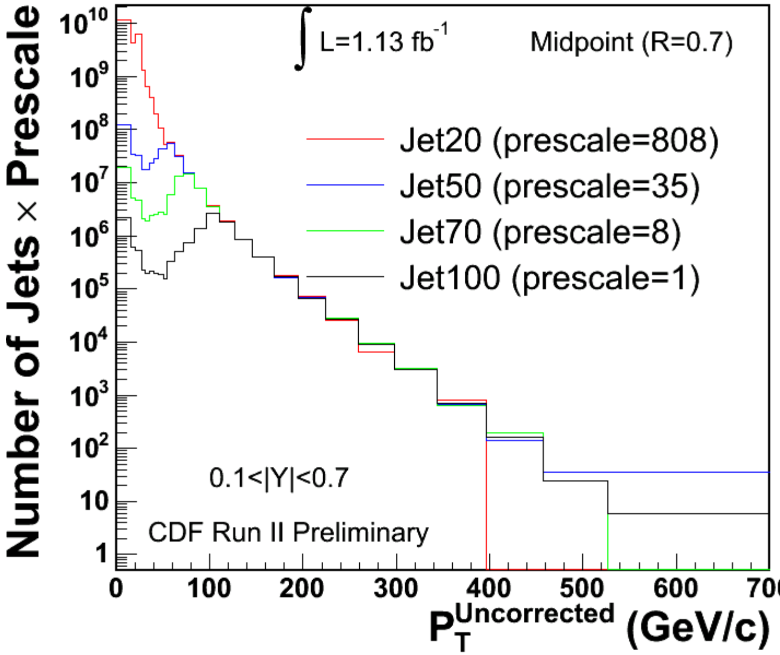
Jet energy resolution: jets move in or out from a bin

- Challenges:
  - Triggering
  - Jet energy scale
  - Unfolding
  - Corrections for non-perturbative effects
  - …

Inclusive Jets at CDF

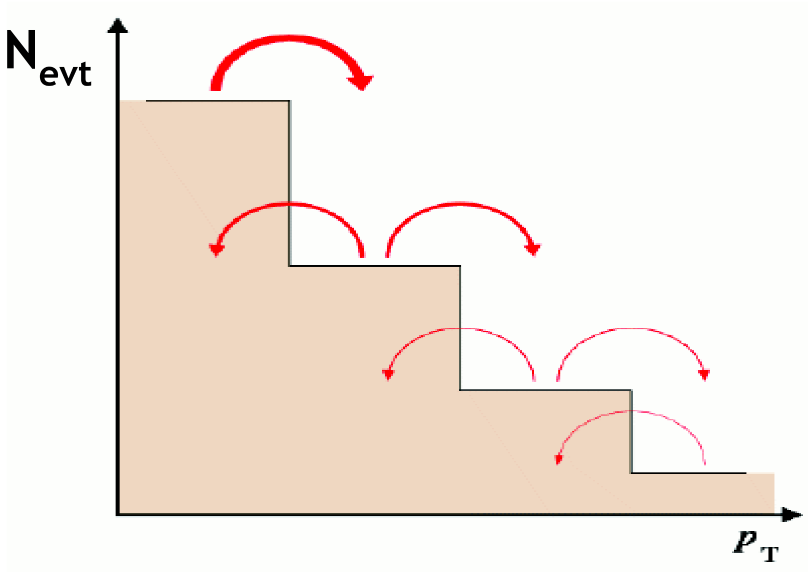
- The measurement spans over 8 orders of magnitude in cross section
- A single trigger (online event selection) system cannot cover all
- Use different trigger samples
  - Trigger on single jets with different Pt thresholds and prescales
- Full Pt spectrum combined from seven different triggers

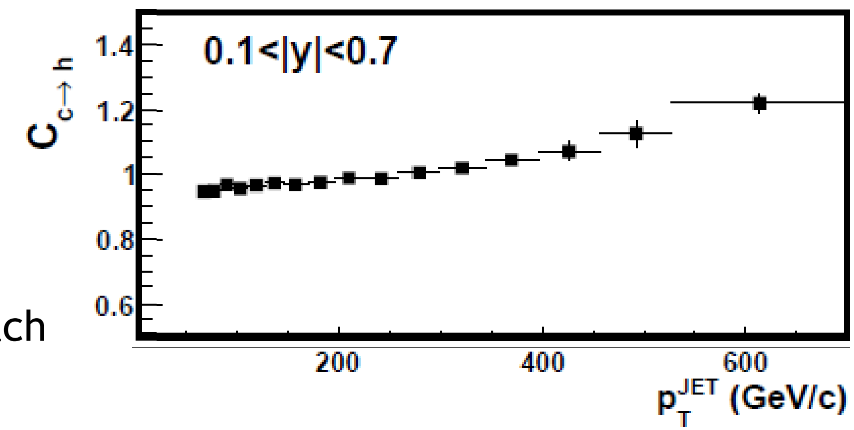




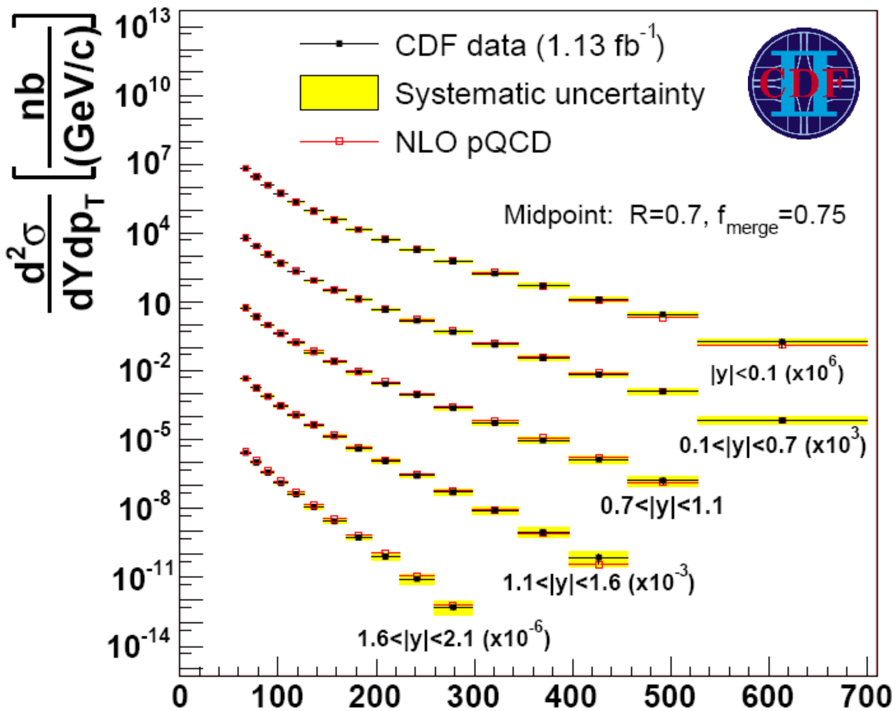
Inclusive Jets at CDF: Unfolding

- Unfolding correction accounts for finite jet energy resolution
  - Jets move in and outside a pt and y bin due to a finite resolution
  - A steeply falling spectrum gets gets affected
- There are several unfolding techniques:
  - Bin corrections
  - Regularized matrix inversion
  - Bayesian unfolding
- Used the bin correction method
  - Take a “true distribution” from MC
  - Smear it with full detector simulation
  - Reweight MC
  - Take the ratio of true / smeared in each bin – apply to data

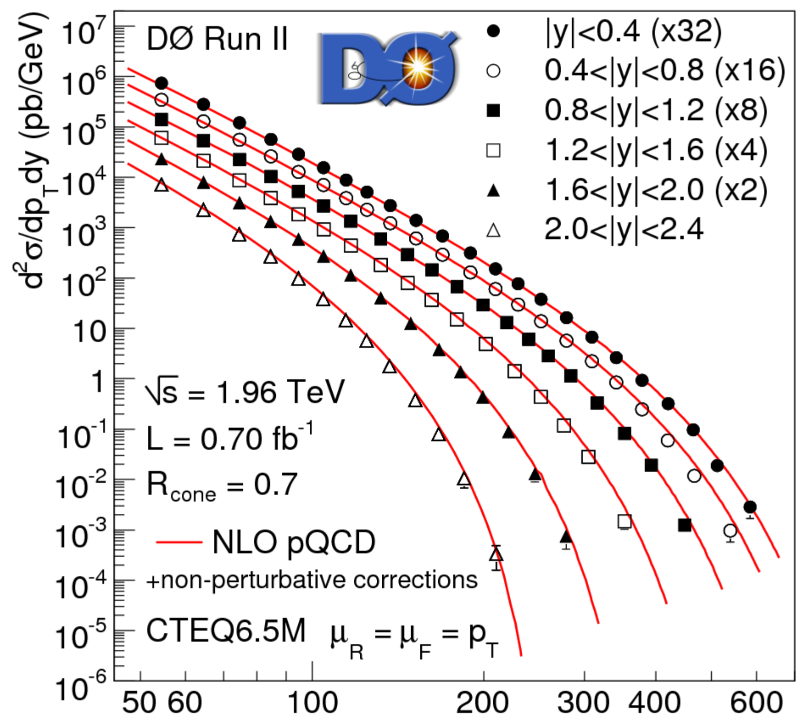




Inclusive Jet Cross Section



PRD 78, 052006 (2008) p_T (GeV/c)

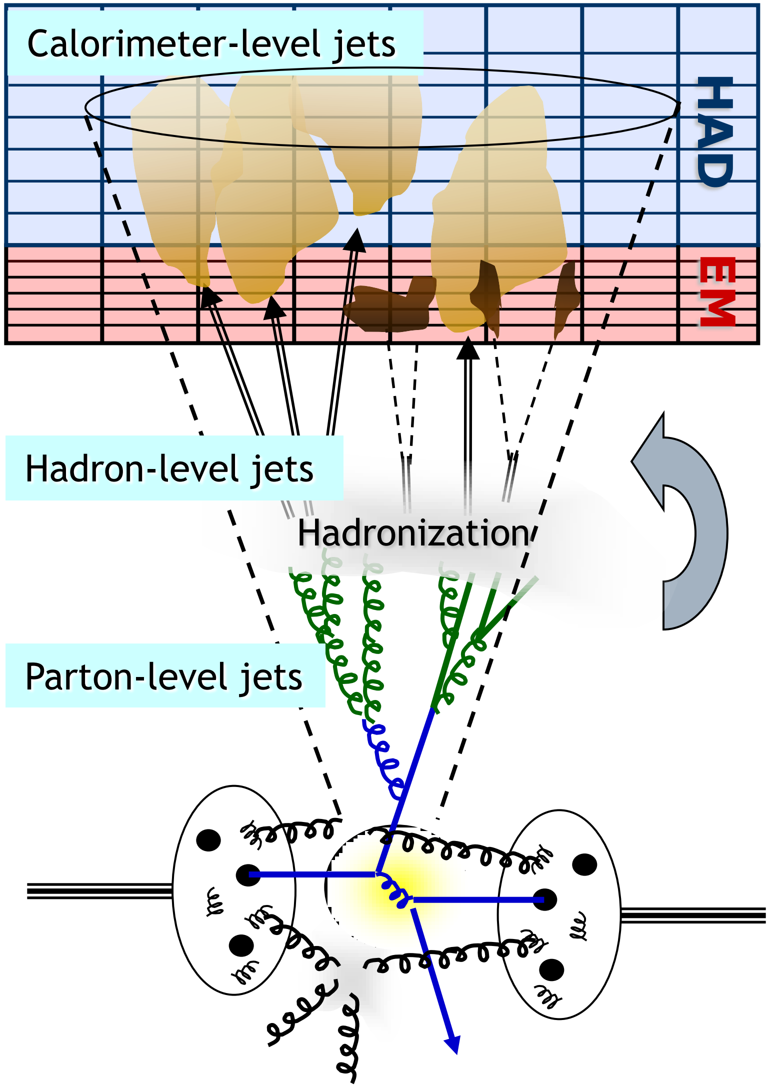


PRL 101, 062001 (2008) p_T (GeV/c)

Results with Kt alorithm PRD 75, 092006 (2007)

- Test pQCD over 8 order of magnitude in $d\sigma^2/dp_Tdy$
- Highest p_T^{jet} > 600 GeV/c: shortest distance scale – soon to be surpassed…

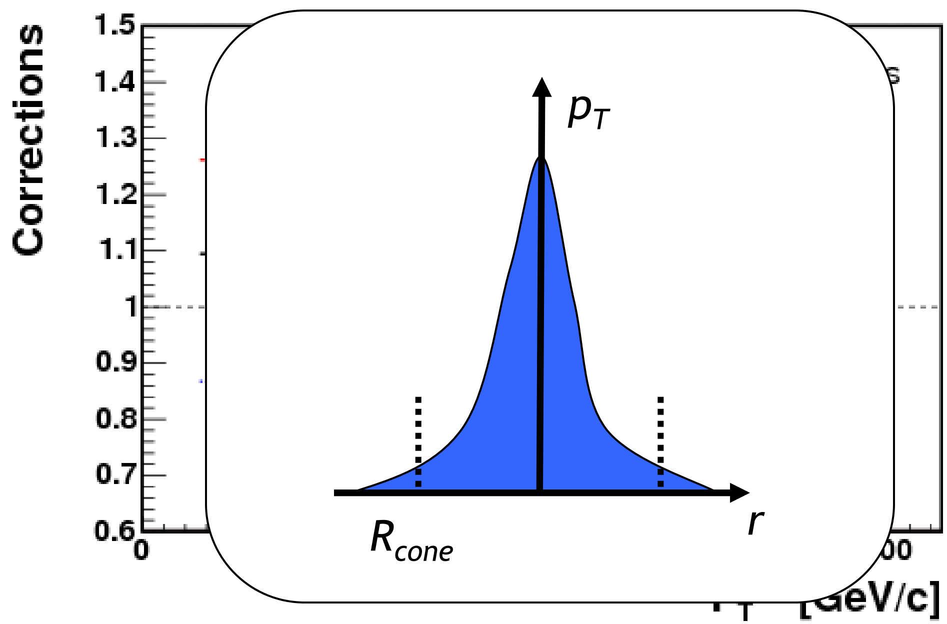
UE & Hadronization Correction



Currently-available state-of-the-art next-to-leading-order QCD predictions do not take into account:

- Underlying event (UE)
- Hadronization

These effects are estimated using Monte Carlo event generator (Pythia) tuned to data.



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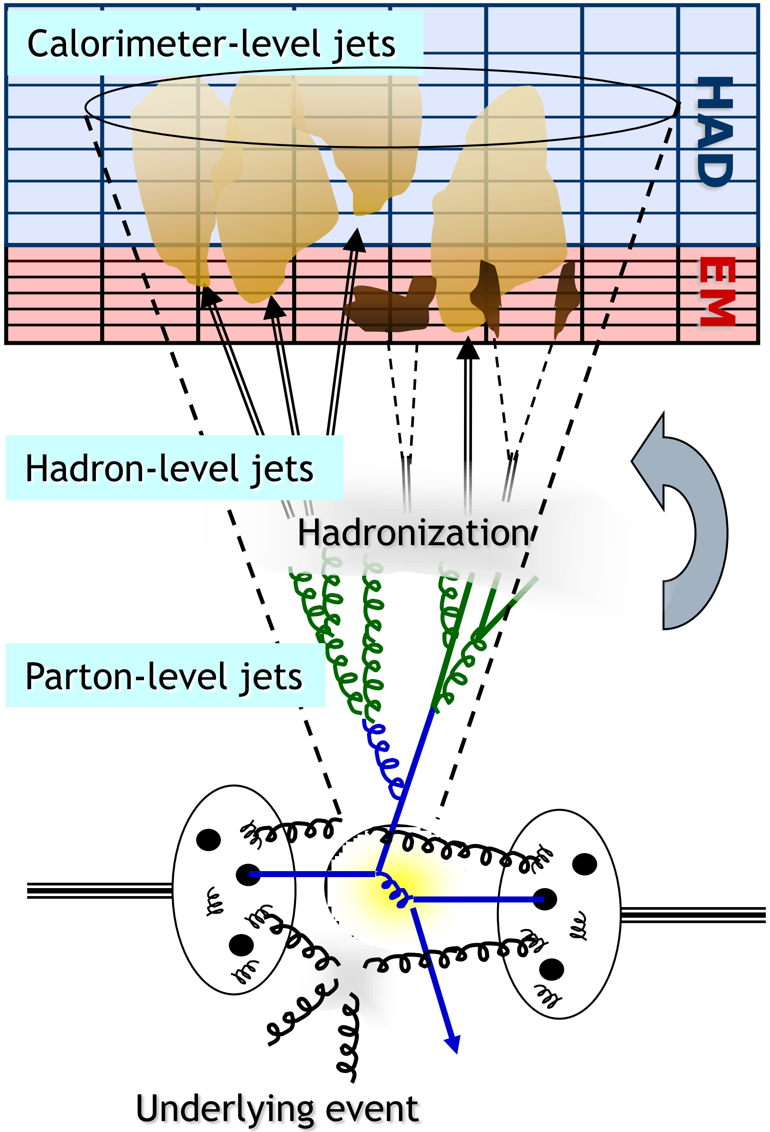

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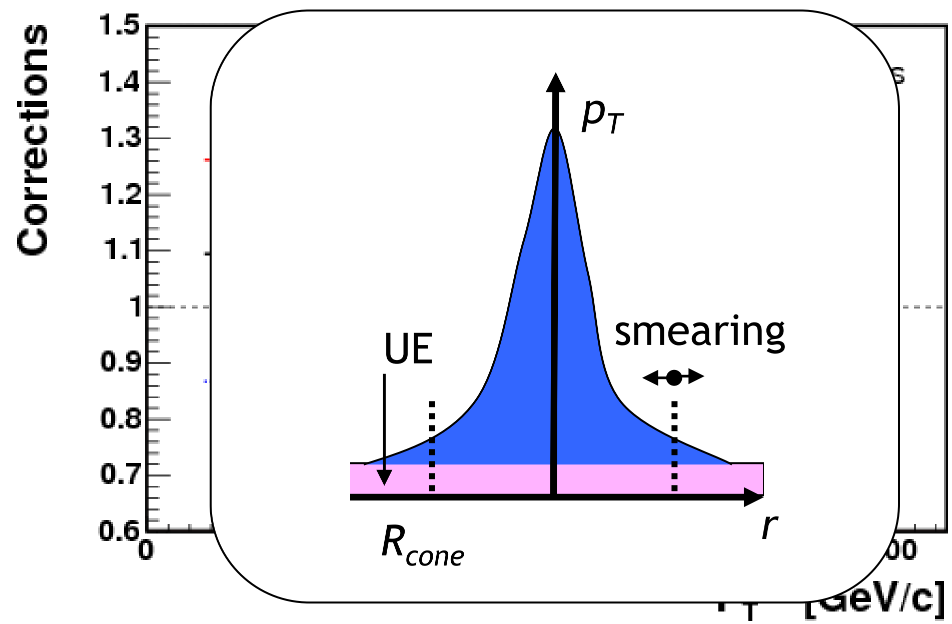

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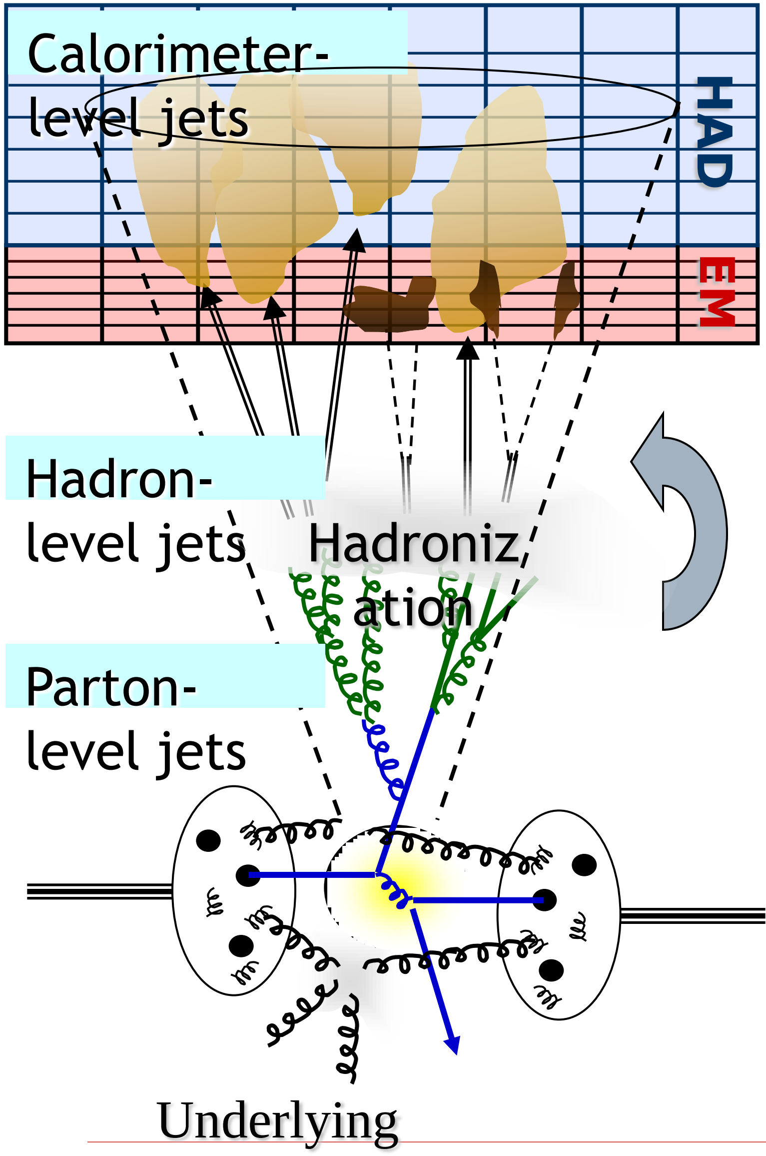

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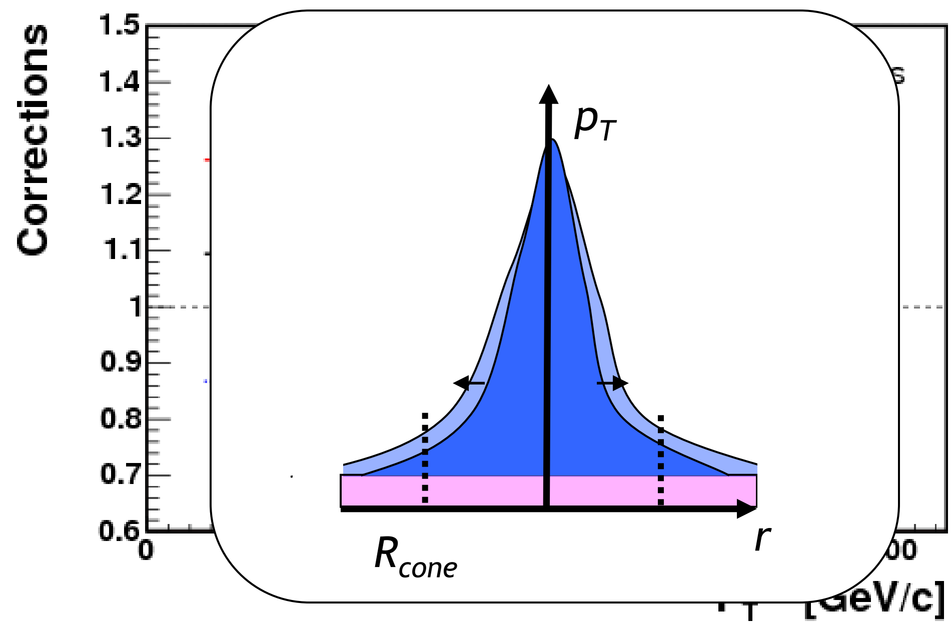
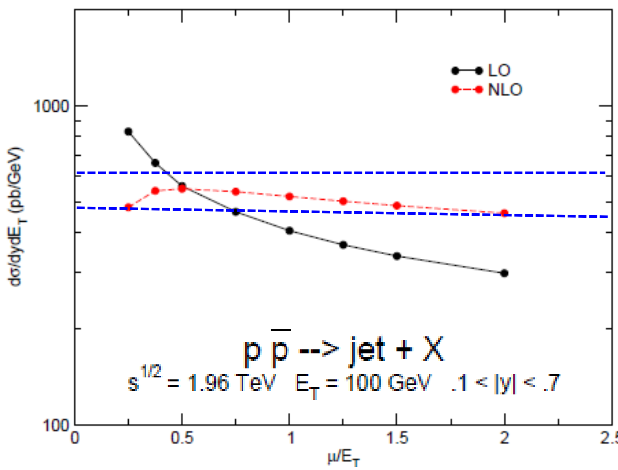


Theoretical Predictions

- The best available theoretical predictions for inclusive jet cross sections at $p\overset{(-)}{p}$ & ep are from next-to-leading order (NLO) pQCD
  - S. Ellis, Z. Kunszt, and D. Soper, PRL 64, 2121 (1990).
  - W. Giele, E. Glover, and D. Kosower, NPB 403, 633 (1993).
  - Z. Nagy, PRD 68, 094002 (2003).

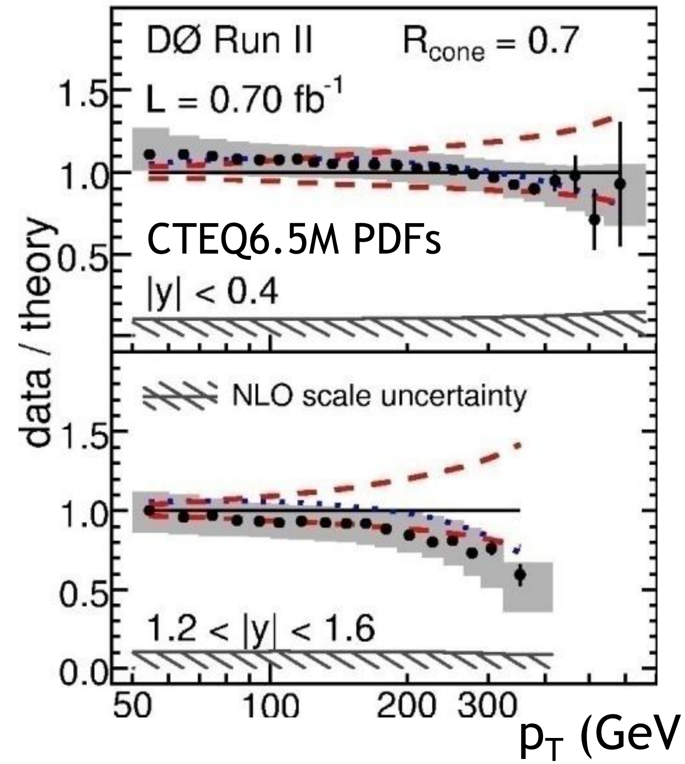


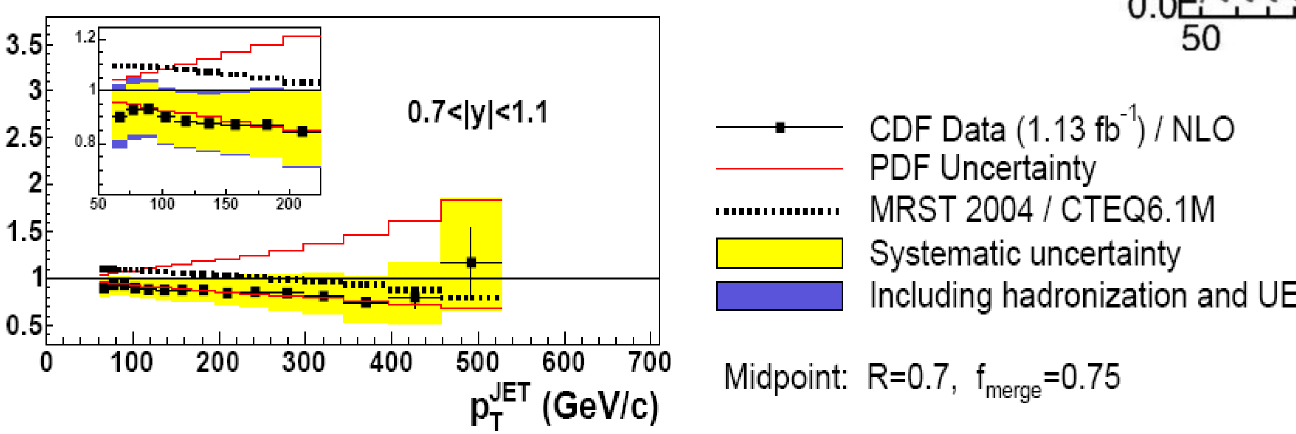
~±10%

- Next-to-next leading order pQCD predictions have been in "will come soon" for quite some years.
  - 2-loop ($O(\alpha_s^4)$) term from threshold corrections (N. Kidonakis, J. F. Owens, PRD 63, 054019) is available and used in some analysis

Inclusive Jet Cross Section

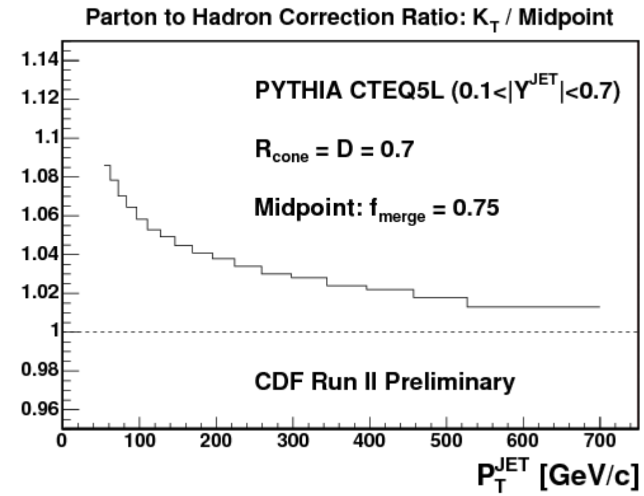
- Run II Tevatron measurements are in agreement with NLO predictions
  - Both in favor of somewhat softer gluons at high-x
- Experimental uncertainties: smaller than PDF uncertainties
- Used in recent global QCD fits





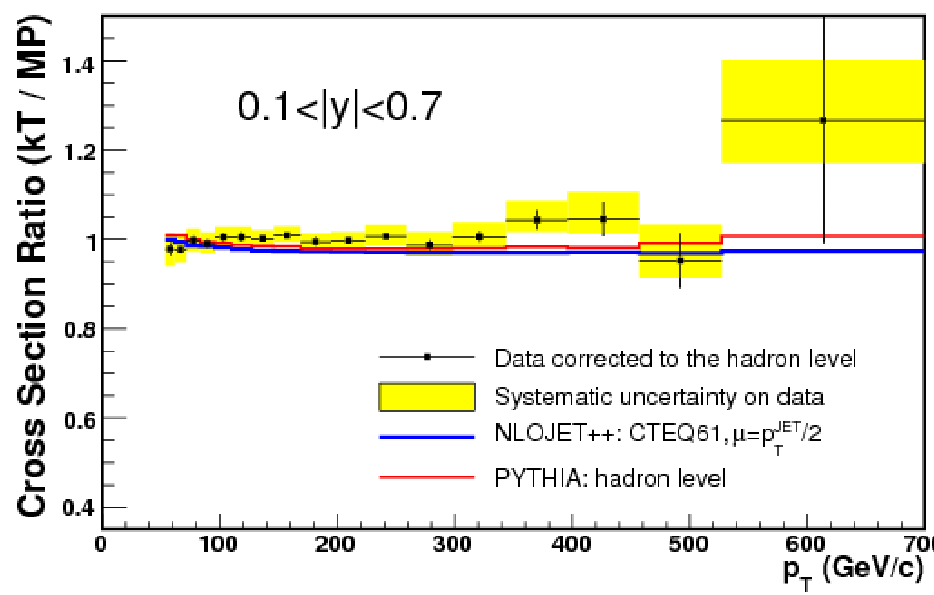
Cone versus Kt Algorithm Results

- At the parton level, $\sigma(k_T)<\sigma(\text{cone})$ with $R_{cone}=D$.
  - Cone algorithm tend to merge two energetic clusters with large separation (>R_{cone}=D) more than the k_T algorithm.

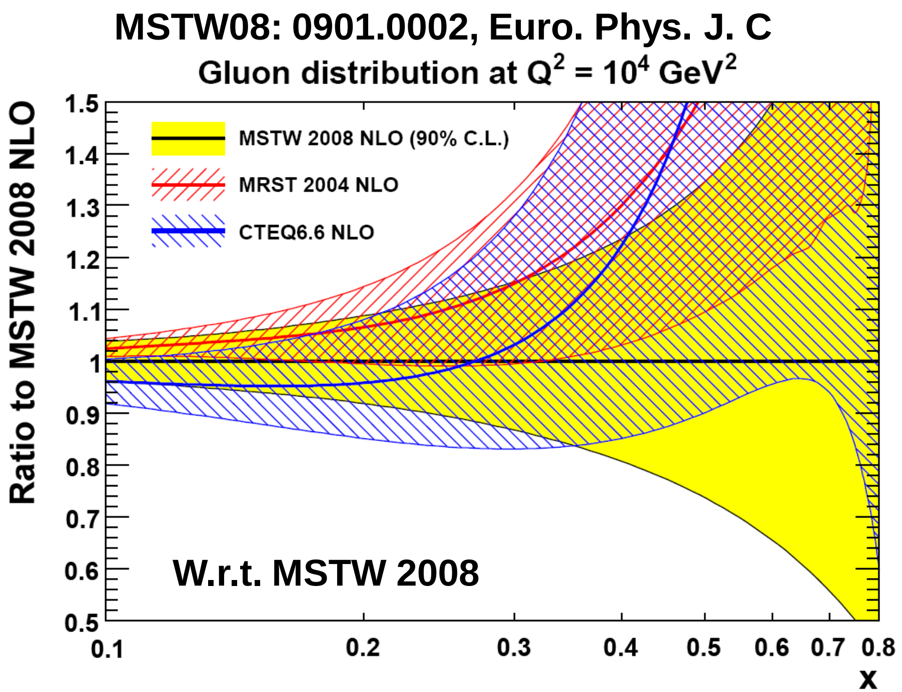


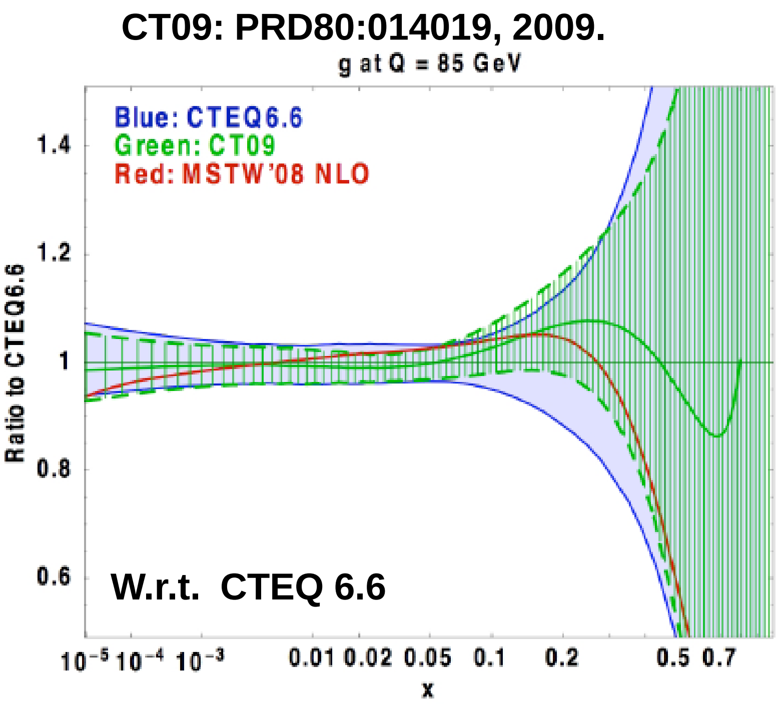
- Non-pertubative (UE+hadronization) effects larger for the k_T algorithm
  - $\sigma(k_T)$ ~ $\sigma(\text{cone})$ at the hadron level.

Measured $\sigma(k_T)$ / $\sigma(\text{cone})$ in general agreement with the expecation.
Robust data-theory comparisons



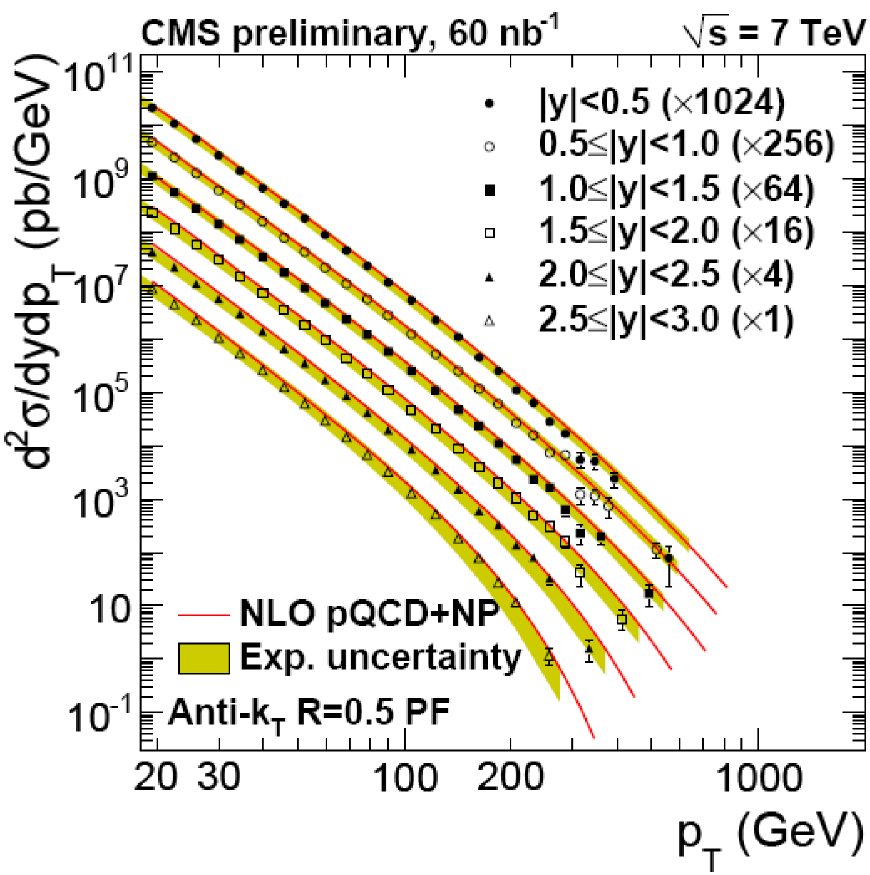
PDF with Recent Tevatron Jet Data



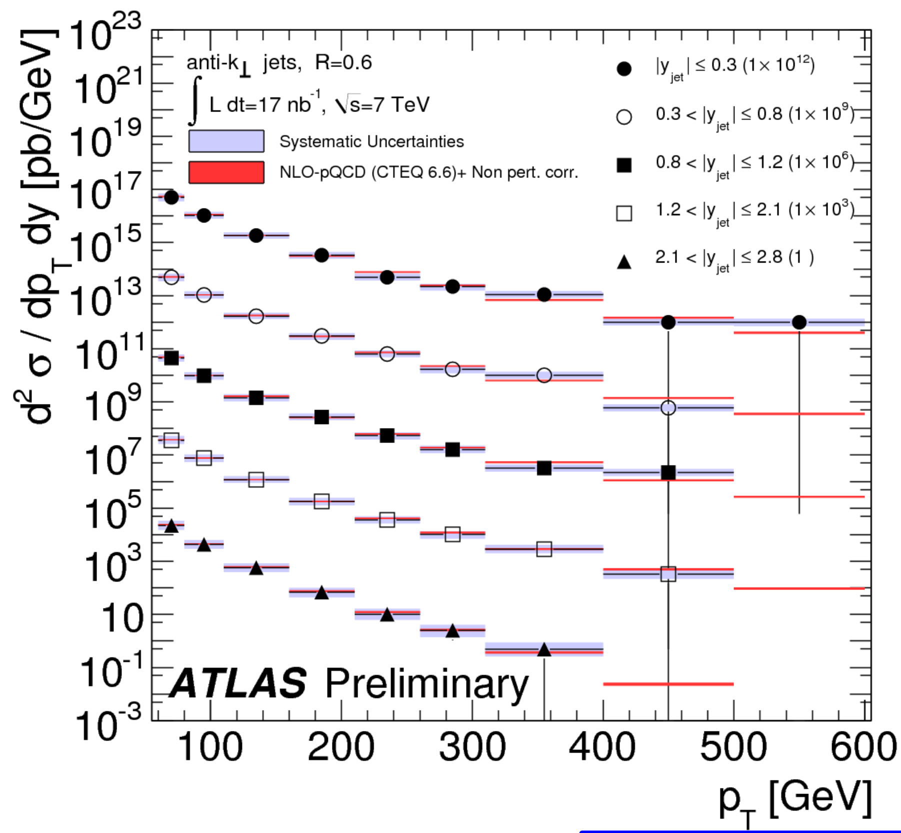


- Tevatron Run II data lead to softer high-x gluons (more consistent with DIS data)

Inclusive Jets at the LHC



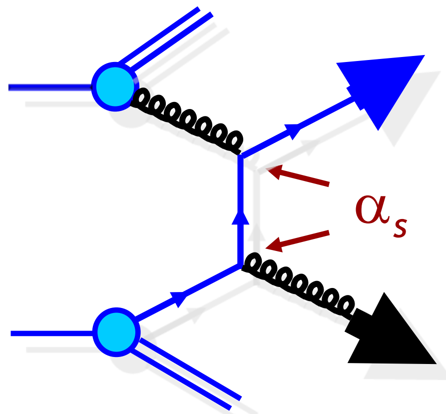
ATLAS-CONF-2010-050



See lecture by K. Rabbertz

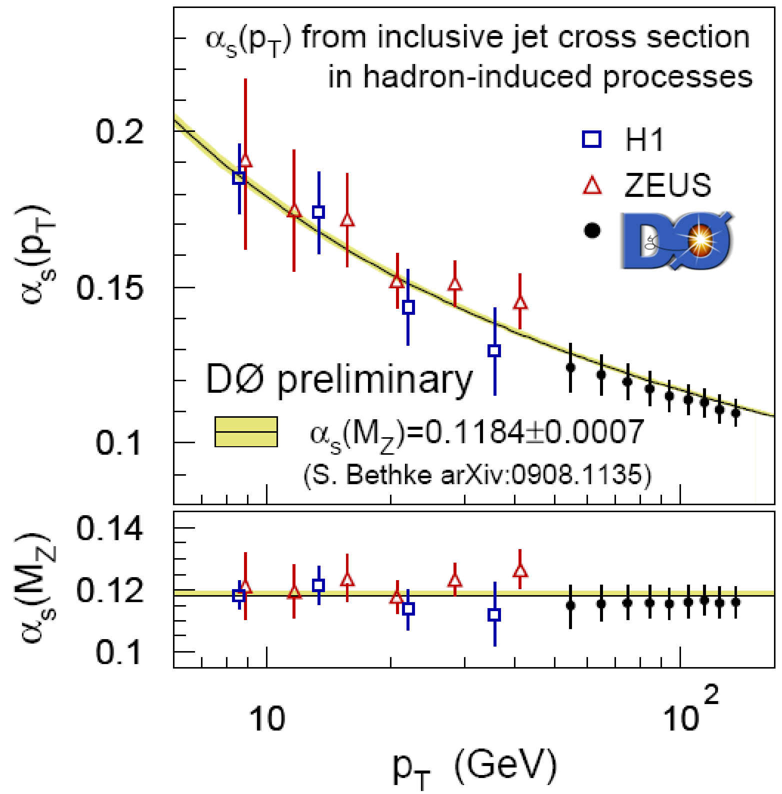
- LHC preliminary results are already becoming available
- Jet energy scale uncertainty 5-10% range (c.f. 1-3% at the Tevatron)

Strong Coupling Constant



$$\sigma_{jet} = (\sum_n \alpha_s^n c_n) \otimes f_1(\alpha_s) \otimes f_2(\alpha_s)$$

PRD 80, 111107 (2009)



- Only data points at $50 < p_T < 145$ GeV/c which do not have much contributions to PDF (x<~0.2) - avoid dependence on PDF
- MSTW2008NNLO PDFs (EPJC 64,653) [α_s(Mz)=0.107-0.127 (21 sets)]
- NLO + 2-loop threshold corrections
- Extend HERA (& e^+e^-) results to high Pt (highest scale α_s so far)

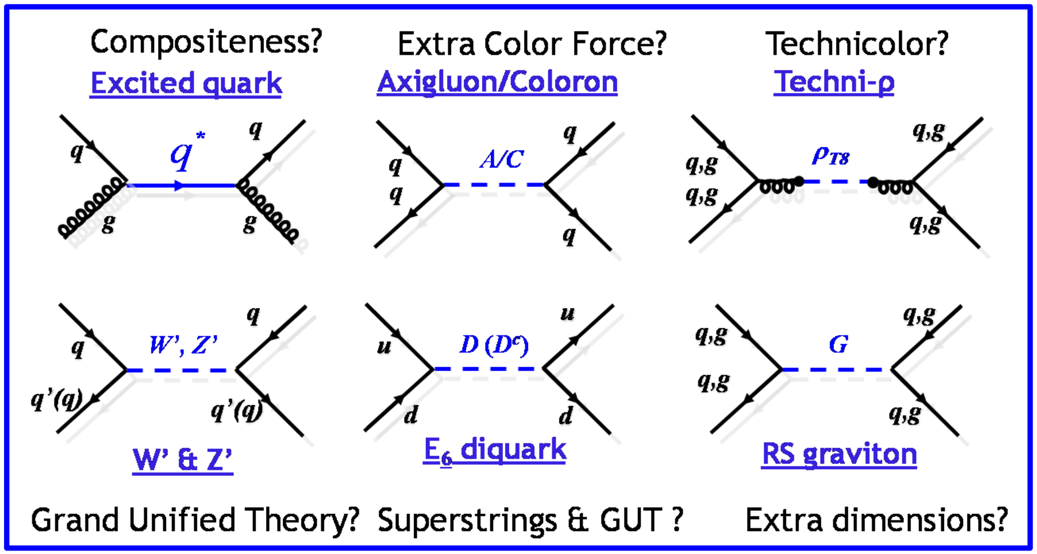
$$\alpha_s(M_Z) = 0.1161^{+0.0041}_{-0.0048}$$

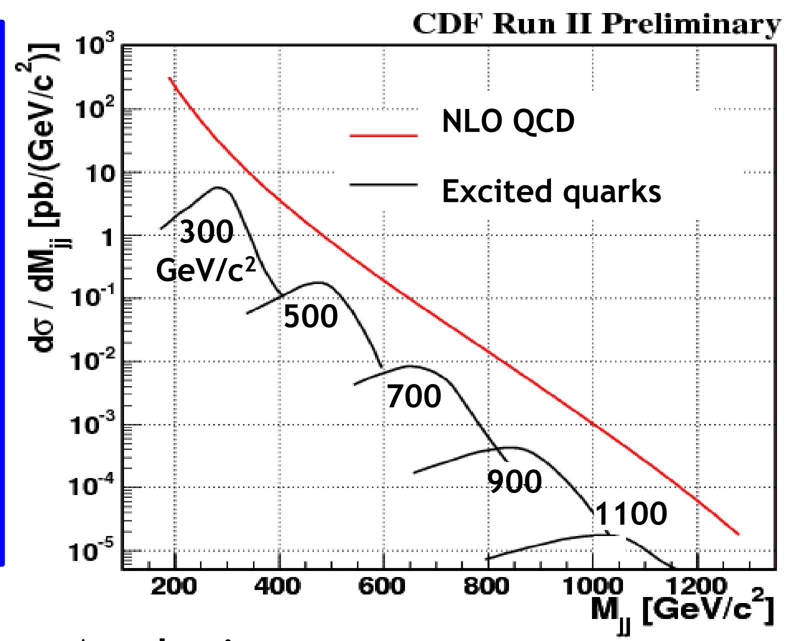
3.5-4.2% precision

New Physics Searches with Jets

Dijet Mass Resonance Search

- Dijet Resonances are predicted in many new physics models.





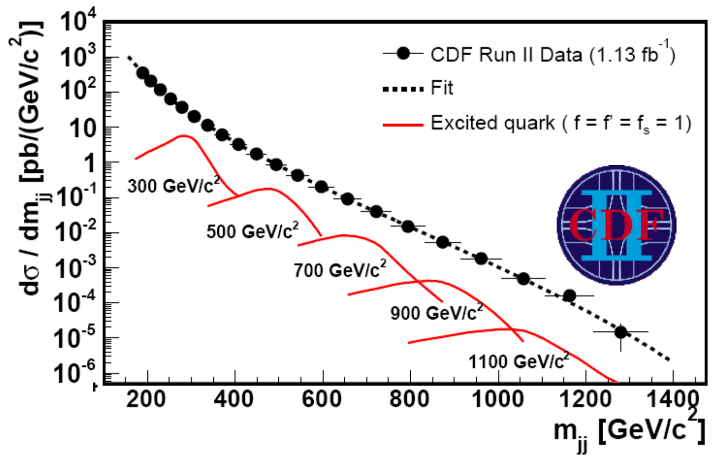
- Recent theoretical development: String Resonances
  - Regge excitations of quarks and gluons
  - Much higher cross-section than excited quark models by a factor ~25 (due to color, spin and chirality effects)

Analysis strategy:
Simple bump hunt over a smoothing falling spectrum

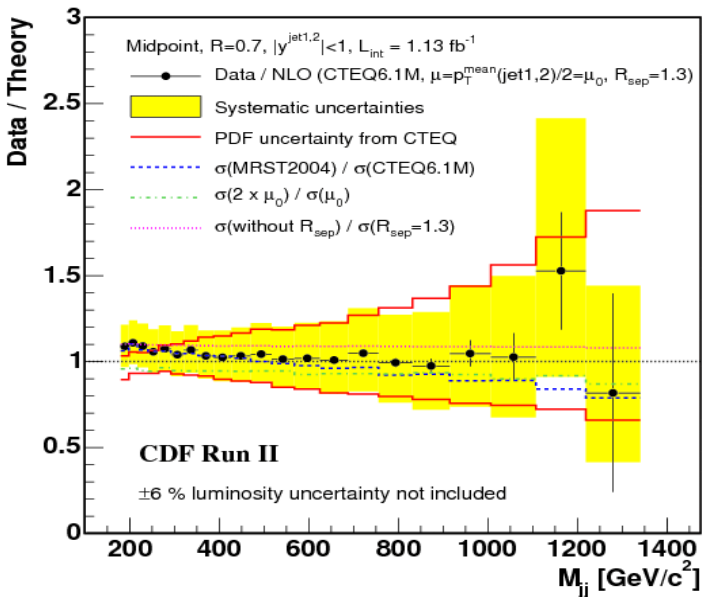
Dijet Mass Spectrum

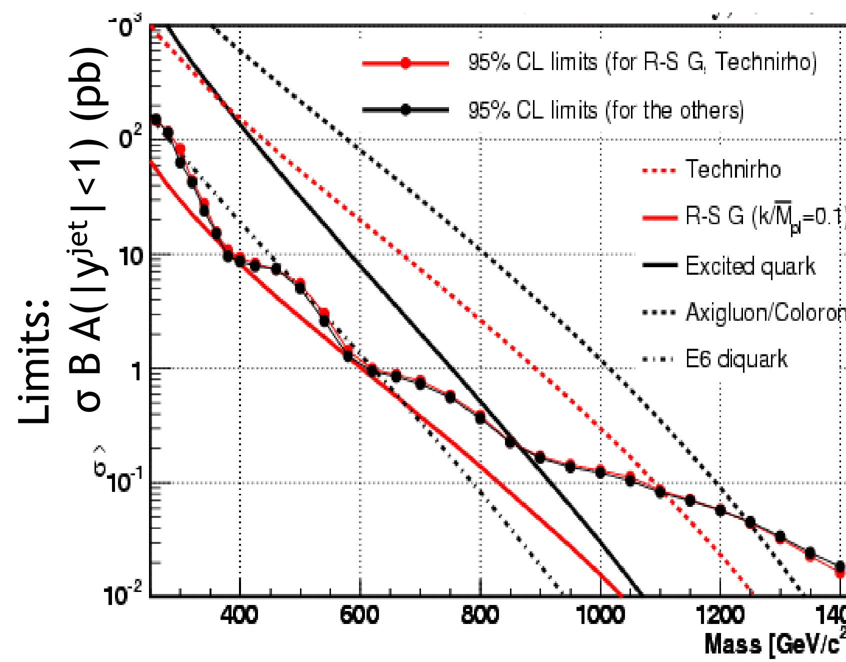
Phys. Rev. D 79, 112002 (2009)

- Consistent with QCD – no resonance
- Most stringent limits on many new heavy particles until last week

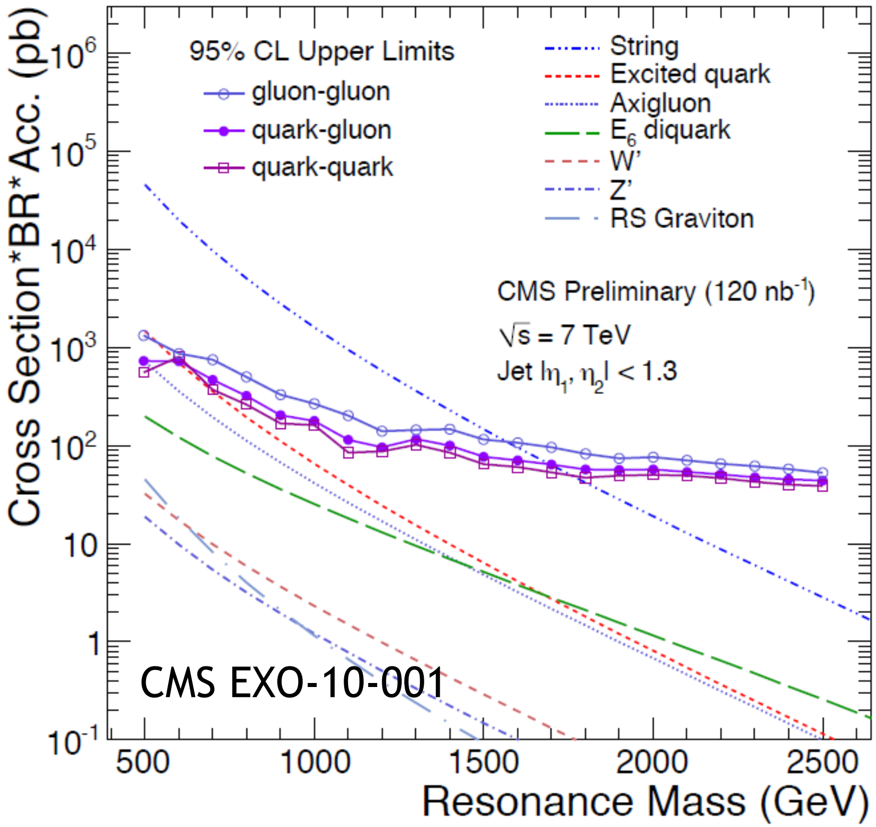


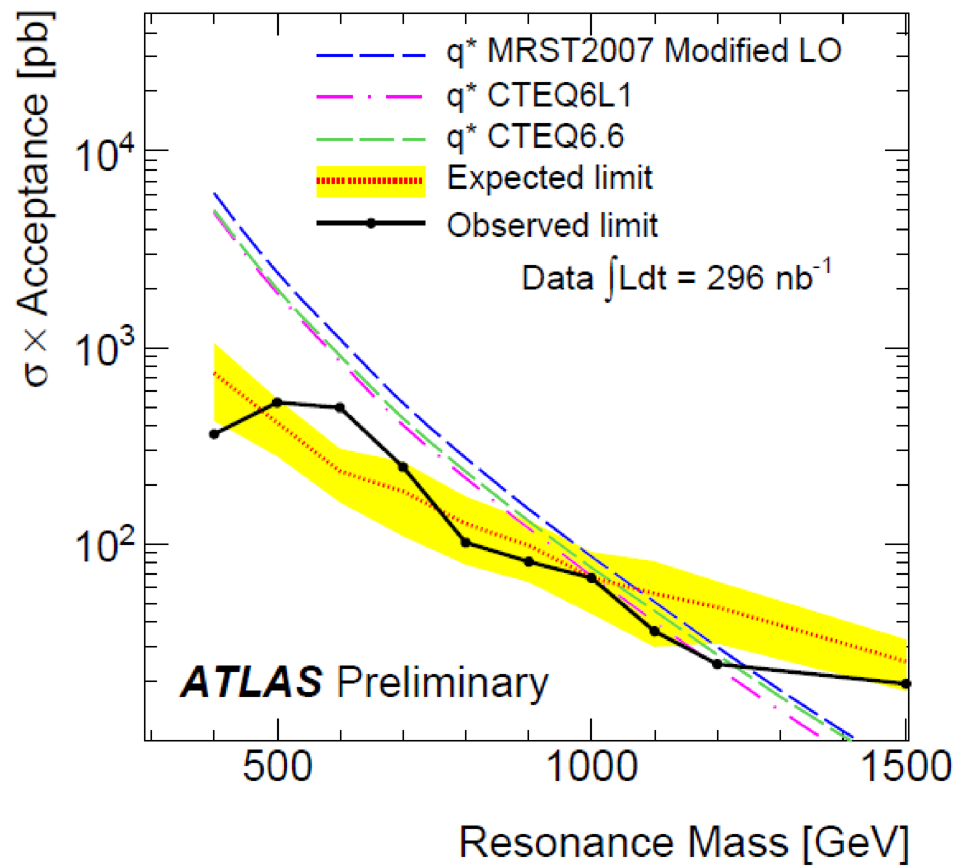
Dijets with jets $|y^{jet}|<1$





Results from the LHC

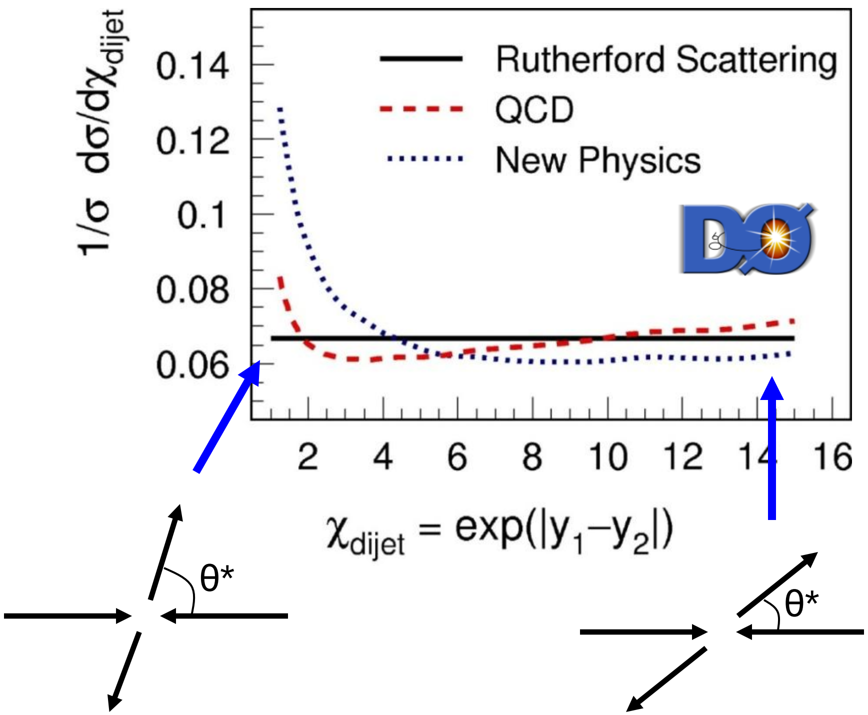




- Similar analyses at the LHC already started to surpass the Tevatron mass exclusions with ~300 nb^{-1}
  q* mass limit: 870 GeV from CDF, 1.29 TeV from ATLAS

See lecture by K. Rabbertz

Dijet Angular Distribution



Variable:

$$\chi_{dijet} = \exp(|y_1 - y_2|)$$

at LO, related to CM scattering angle

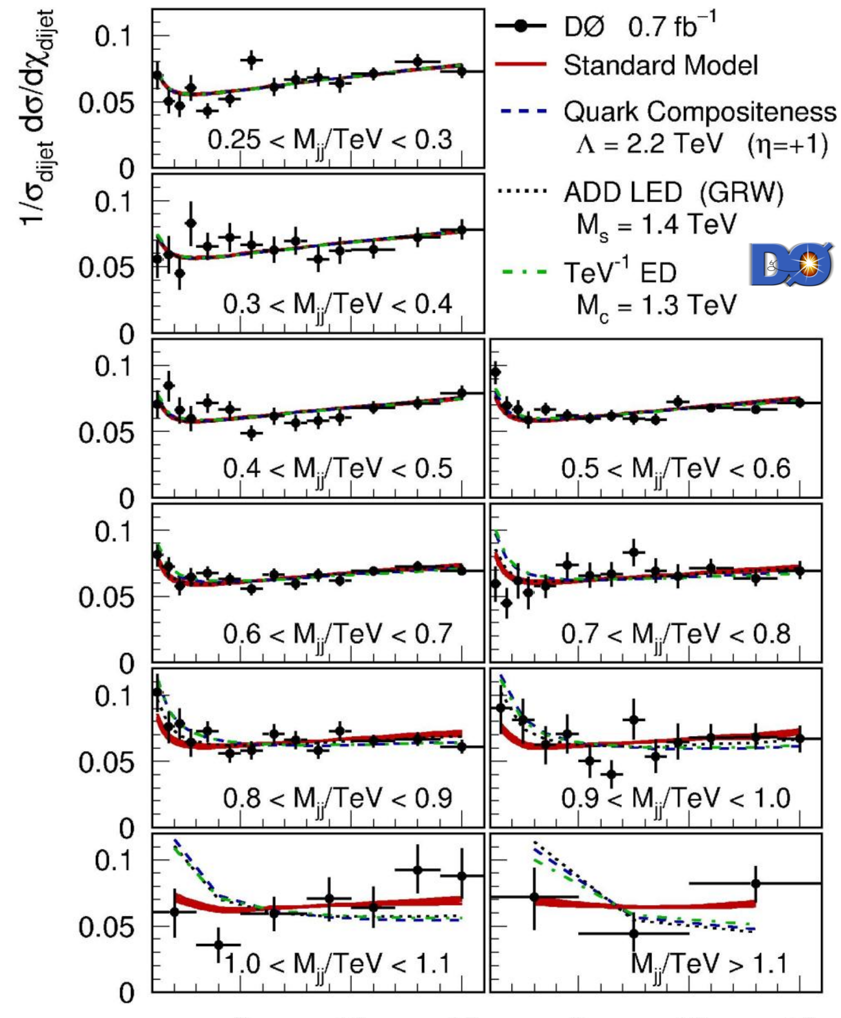
$$\chi_{dijet} = \frac{1+\cos\theta^*}{1-\cos\theta^*}$$

- QCD scattering ~ flat in χ_{dijet}
- New physics, like
  - quark compositeness
  - extra spatial dimensions (LED)
  - → Peak centrally (low χ_{dijet})

$\frac{1}{\sigma}\frac{d\sigma}{d\chi_{dijet}}$: Normalized distribution (reduce experimental and theoretical uncertainties)

Dijet Angular Distribution

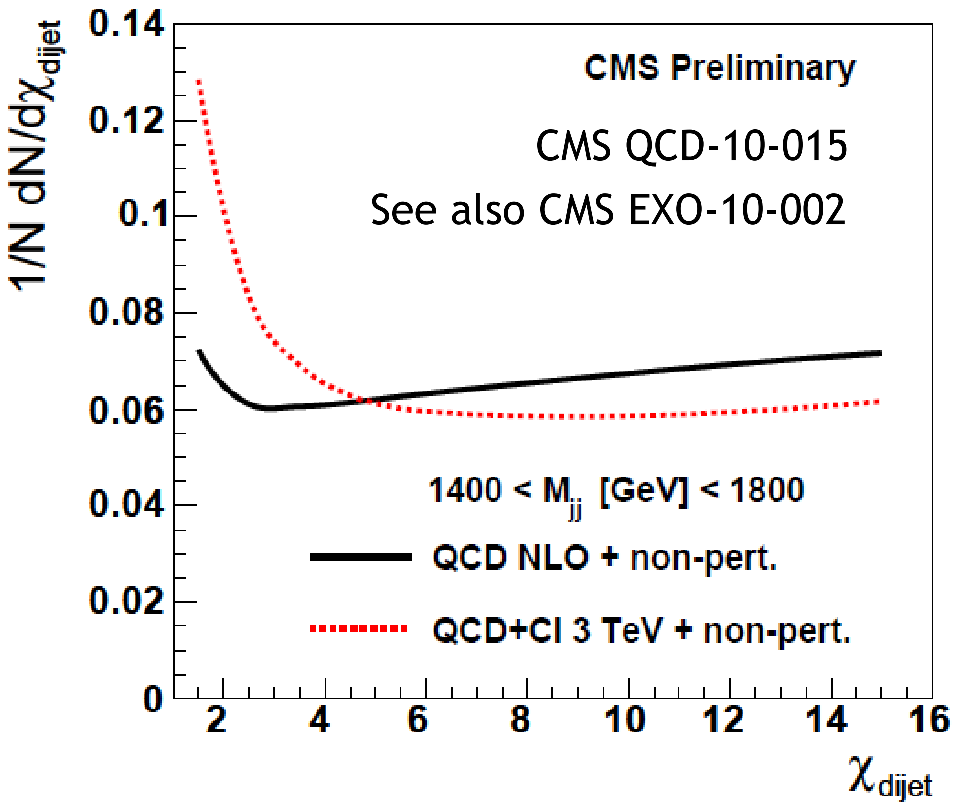
$$\frac{1}{\sigma}\frac{d\sigma}{d\chi_{dijet}}$$: Normalized distribution (reduce experimental and theoretical uncertainties)

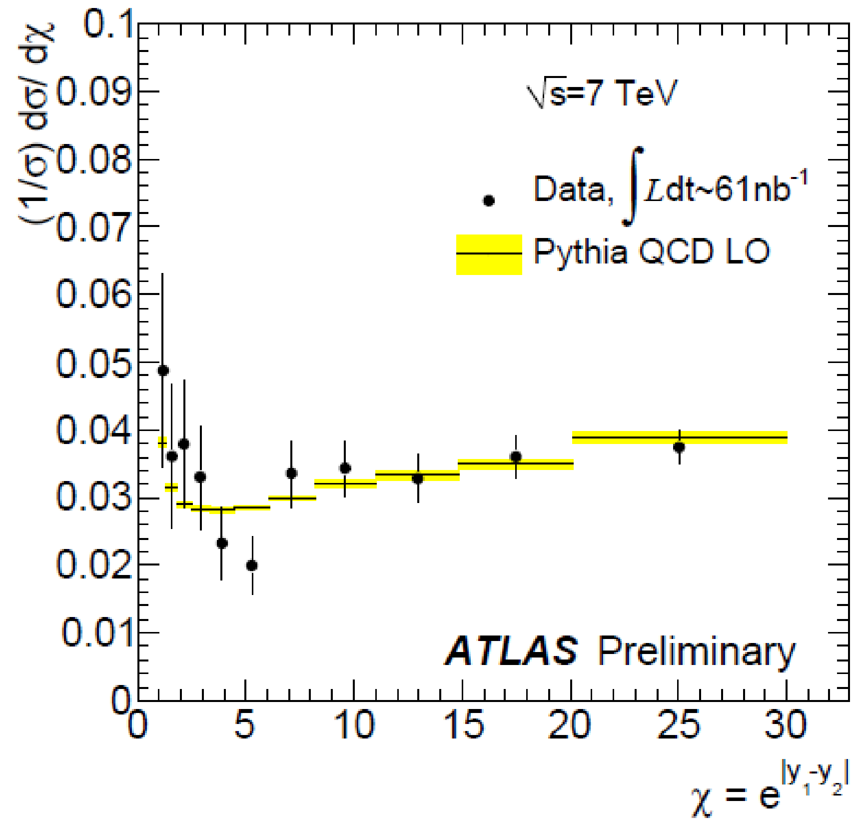


- ☐ Consistent with NLO pQCD
- ☐ Limits on Compositeness & LED
  - Quark Compositeness Λ > 2.9TeV
  - ADD LED (GRW) Ms > 1.6 TeV
  - TeV-1 ED Mc > 1.6 TeV

Jet Physics at the Tevatron, A. Bhatti, Don Lincoln, arXiv:1002:1708

Results from the LHC





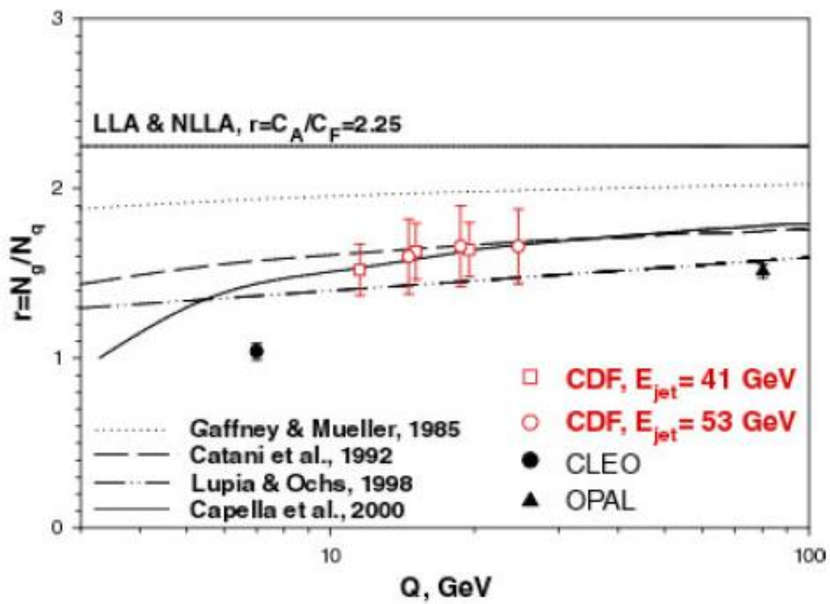
- LHC will become competitive with the Tevatron limit of Λ > 2.8 TeV (D0, 1fb-1) with 4 pb^{-1}

See lecture by K. Rabbertz

Jet Fragmentation

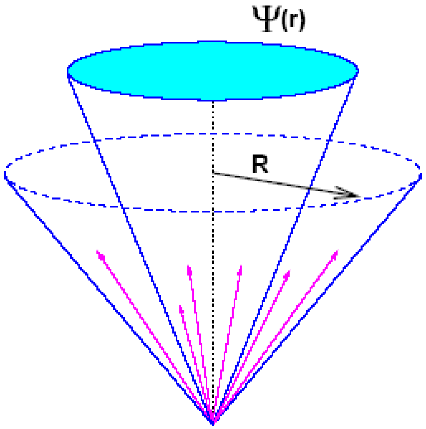
Particle Multiplicities in Quark & Gluon Jets

- Difference of particle multiplicities in gluon and quark jets
  r = Nch(gluon jet) / Nch(quark jet): Naive expectation = $C_A/C_F = 9/4$
- Calculations (for partons):
  - various extensions of NLLA: $r=1.5\text{-}1.7$ (depends on $Q=E_{jet}\theta_{cone}$)
    (differ from 9/4 due to higher order corrections & energy conservation)
- Data: 15+ papers from e+e-
  - r=1.0-1.5 (not all consistent)
- CDF analysis:
  - Dijet events with $M_{jj}\sim100$ GeV
    gluon jet fraction ~ 60%
  - γ-jet events with $M_{\gamma j}\sim100$ GeV
    gluon jet fraction ~ 20%
  - Measure N_{jj} and $N_{\gamma j}$ inside
    15-30° cone around jet axis
  - Resolve for N_g,N_q and their ratio: $r\sim1.6\pm0.2$



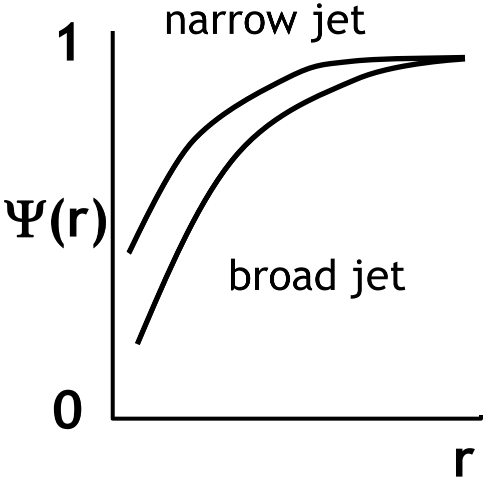
Jet Shape: Energy Flow Inside a Jet

- Integrated jet shape: the average fraction of jet Pt that lies inside a cone of radius r concentric to the jet axis



$$\Psi(r) = \frac{1}{N_{jets}} \Sigma_{jets} \frac{p_T(0,r)}{p_T^{jet}(0,R)}$$

$$r = \sqrt{(\Delta y)^2 + (\Delta\varphi)^2}$$

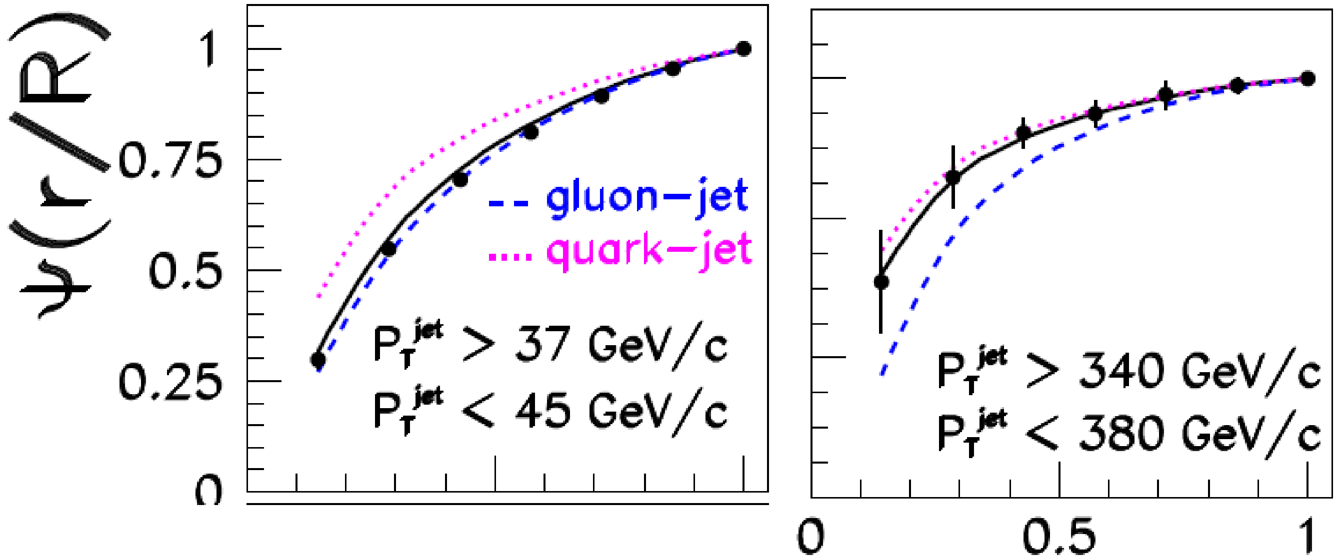


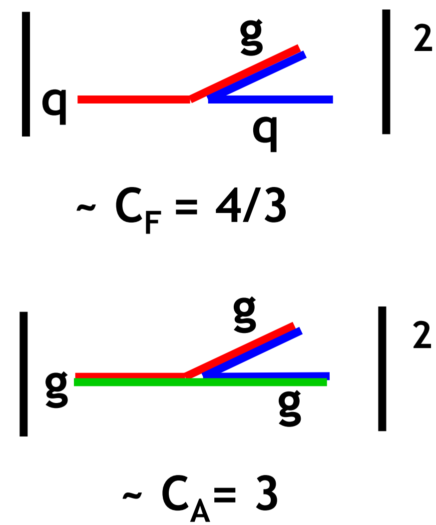
- Give insights into the transition between the parton produced in the hard process and the observed spray of hadrons
- Sensitive to quark / gluon jet differences
- Proper modeling of particle composition, multiplicity, momentum distribution is critical for e.g. jet response modeling in MC:

  2 hadronc with Pt=50 GeV/c ≠ 20 hadrons with Pt=5 GeV

  due to calorimeter non-linearity

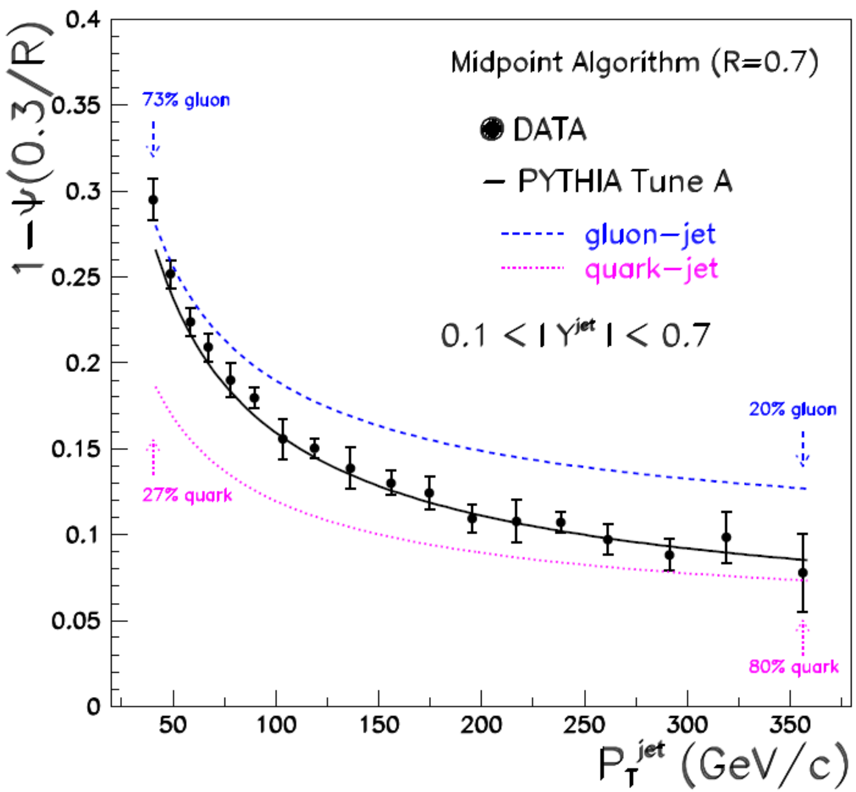
Jet Shape - Gluon vs Quark Jets

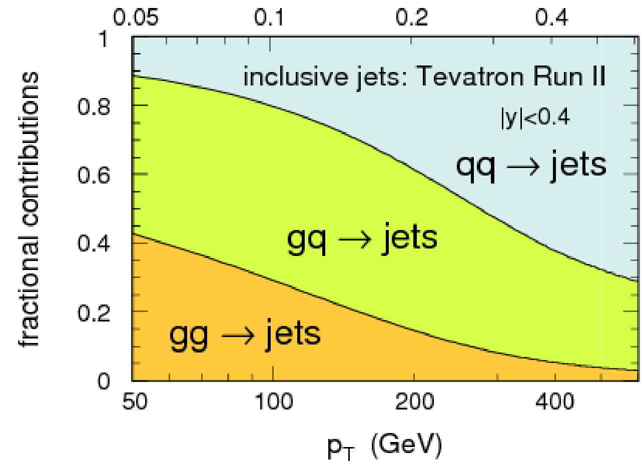


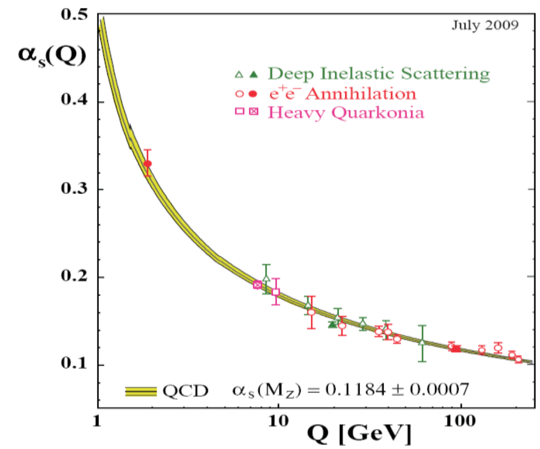


- Gluon jets are broader than quark jets

Jet Shape - Jet Pt Dependence

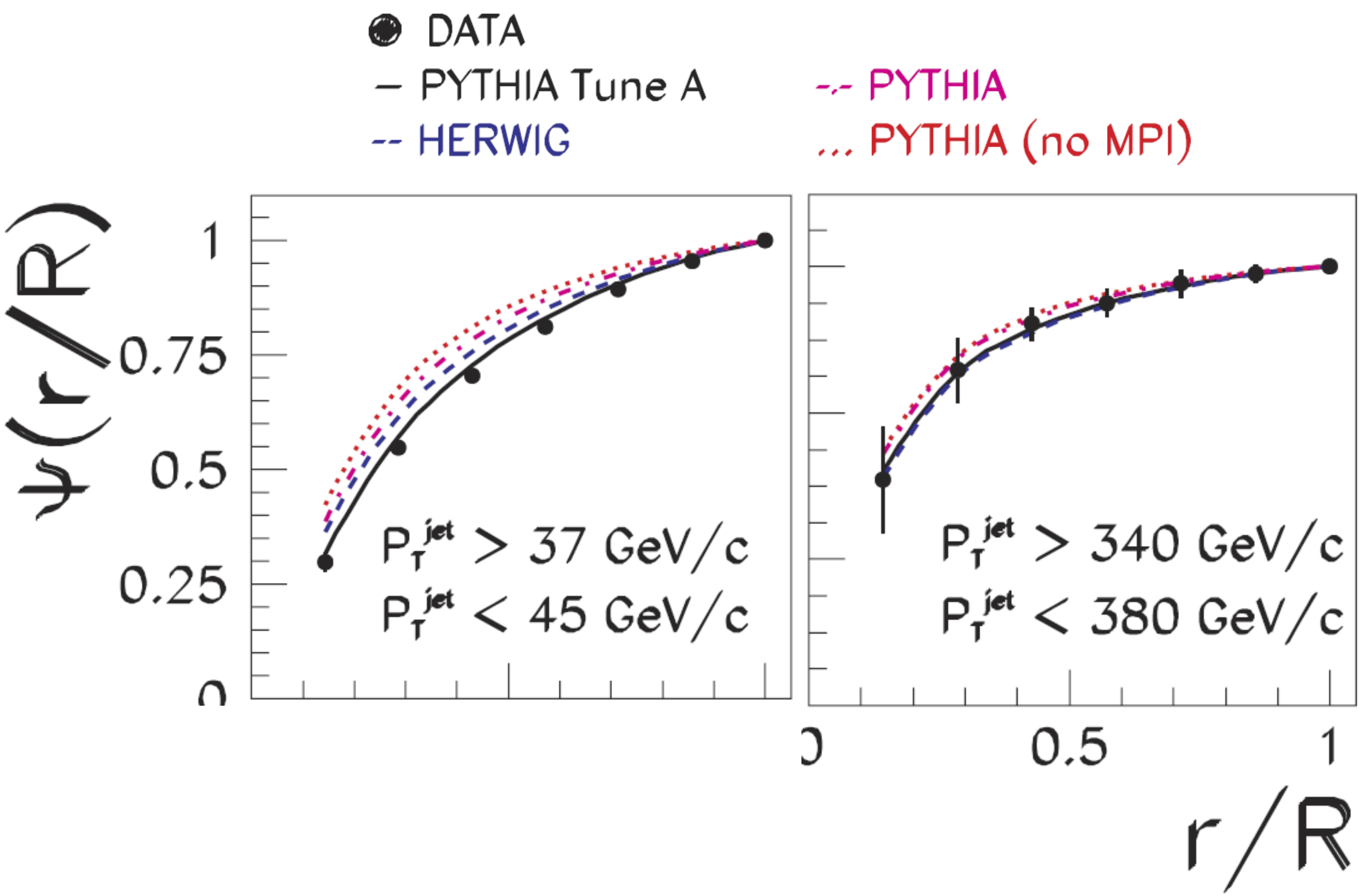






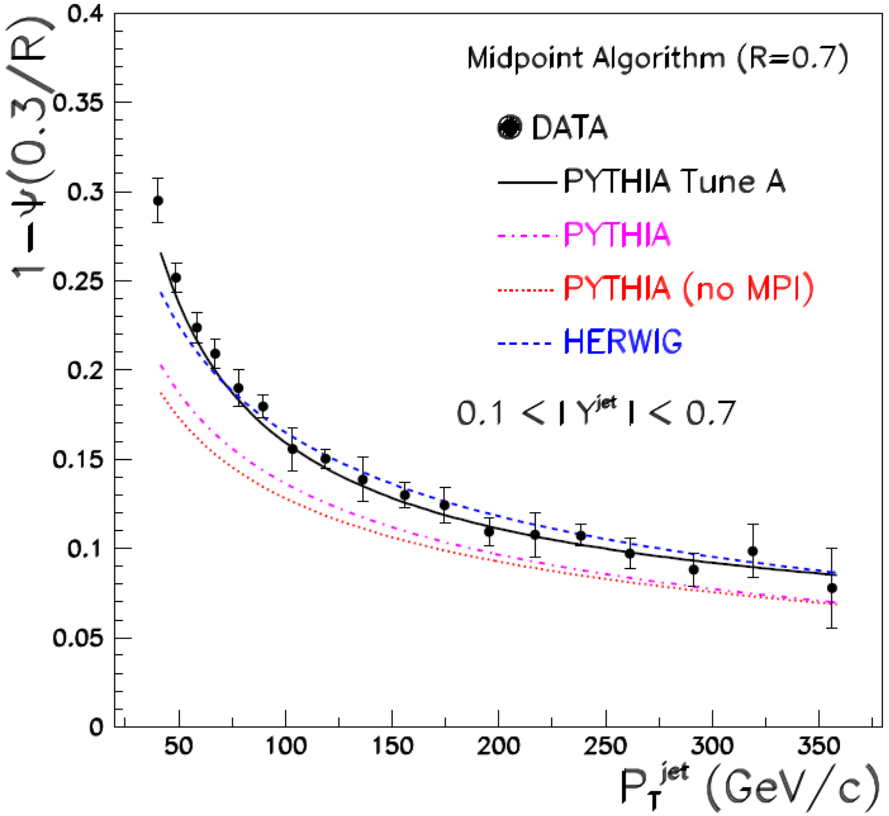
- Gluon jets are broader than quark jets
  - More quark jets at higher Pt in inclusive jet production
- Jets of the same flavor are becoming more collimated at high Pt due to running of α_s

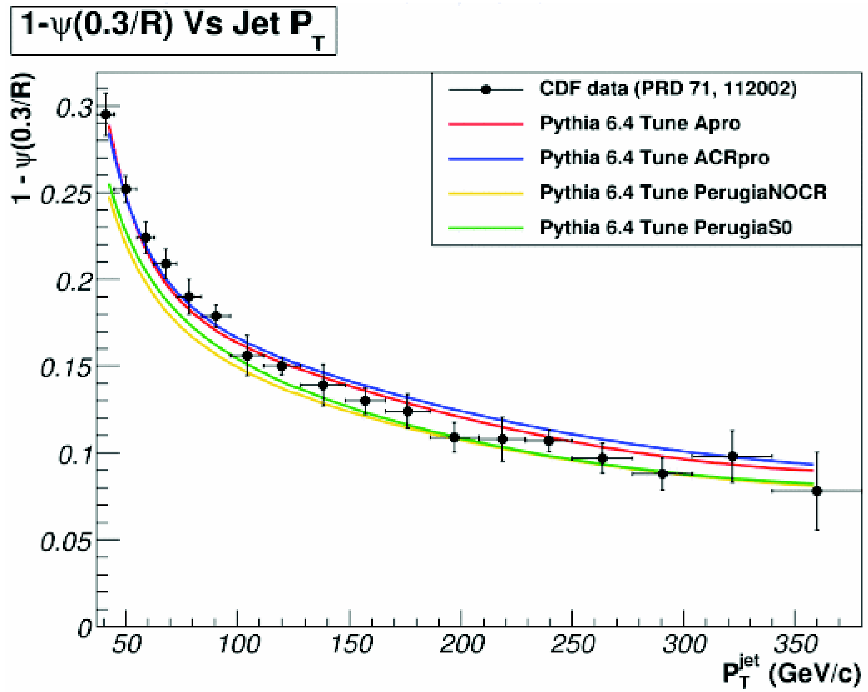
Jet Shape - MC Tunes



- Sensitive to MC parton shower and underlying event model tunings

Jet Shape – MC Tunes



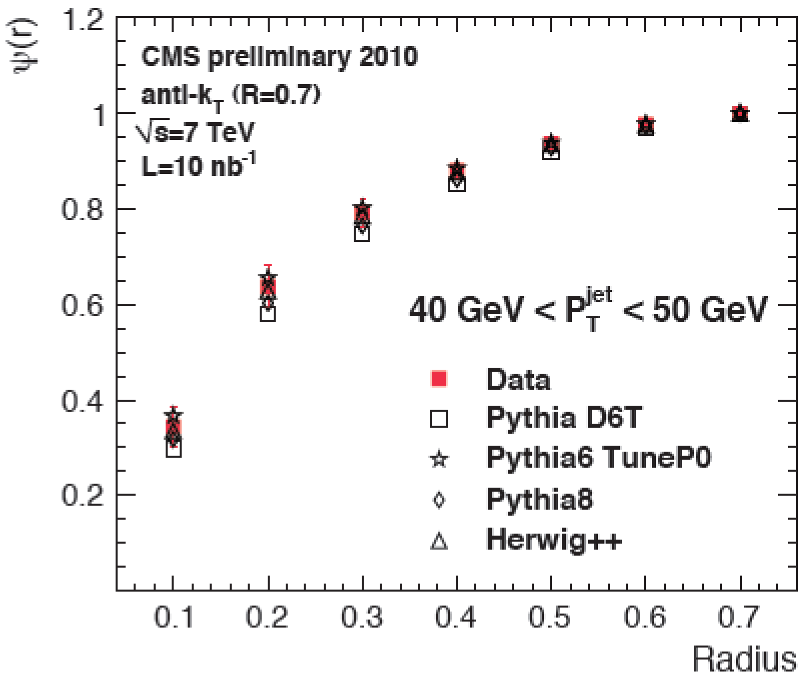


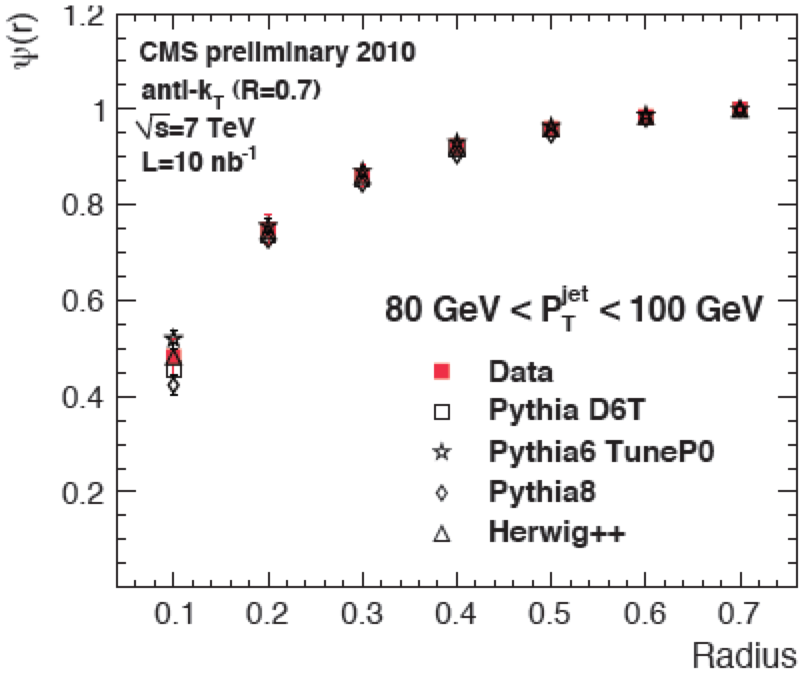
[L. Galtieri's talk at the Tools for LHC Workshop, March 3,2010.]

- Sensitive to Monte Carlo parton shower and underlying event model tunings
  - Cluster frag. (Herwig), string frag. – mass & Pt ordered (Pythia), …
  - Different underlying event tunes

Jet Shape - LHC

CMS QCD-10-014



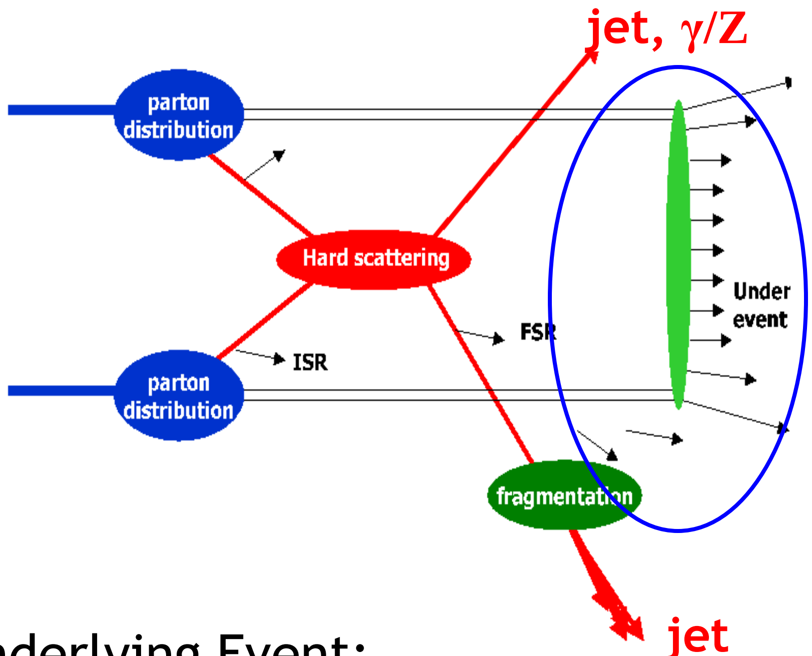


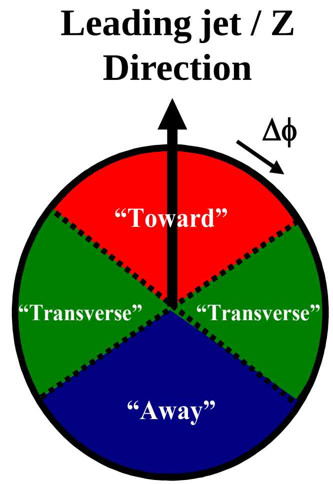
- Need more work on systematic uncertainties to become sensitive to different underlying event tunes

See lecture by K. Rabbertz

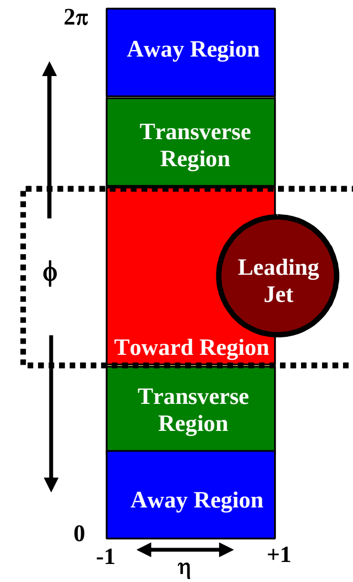
Underlying Event

Underlying Event





Transverse plane



η-ϕ Plane

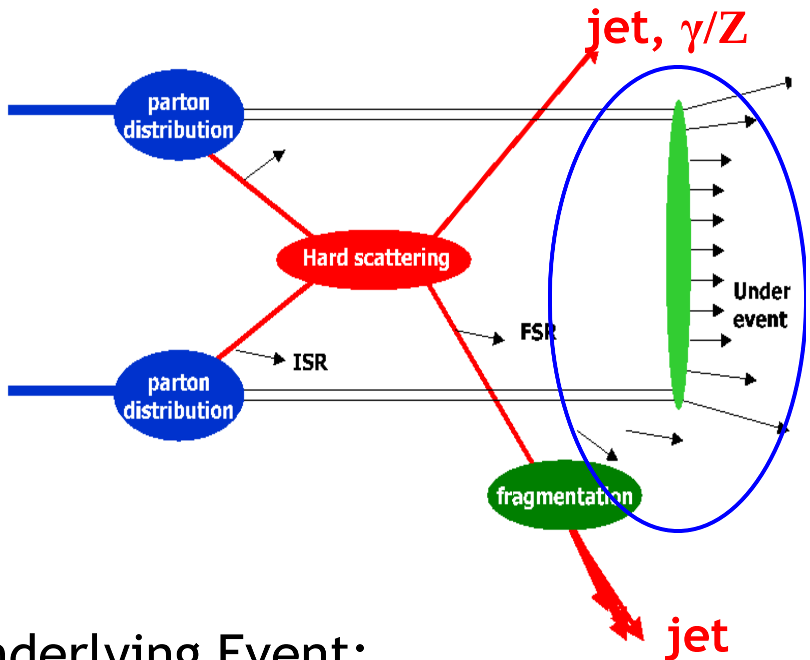
Underlying Event:

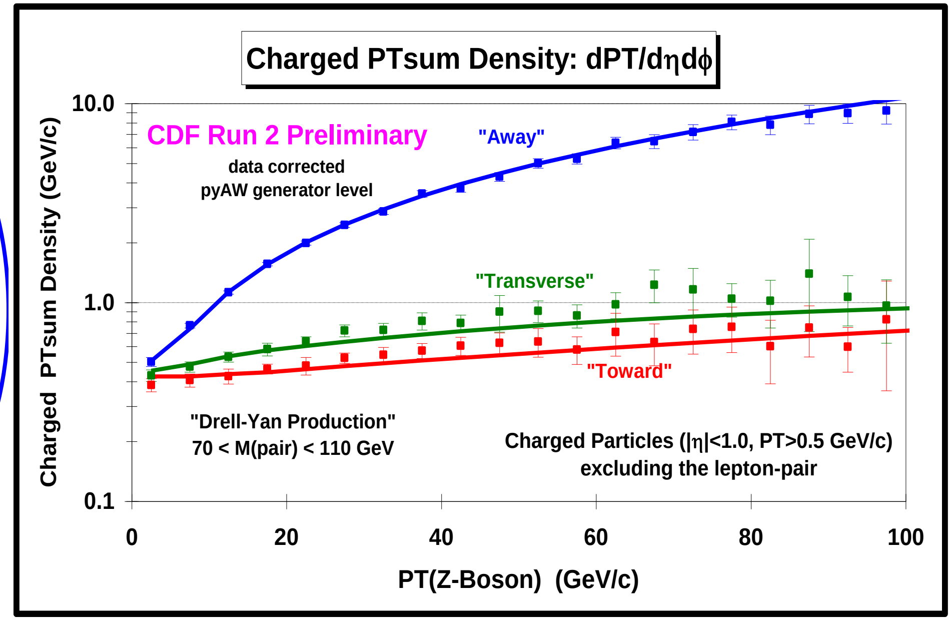
everything except hard scatter

- NOT the same as Min-Bias
- Not independent of hard scatter (includes ISR/FSR/MPI)

- UE contributes to jets
  - Not well understood theoretically (non-perturbative contributions)
- Good model essential for jet physics

Underlying Event





Underlying Event:

everything except hard scatter

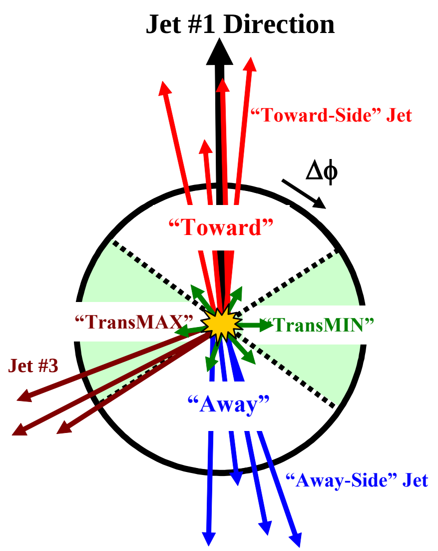
<u>Jet production:</u>

- Transverse region sensitive to UE
- High statistics jet sample
- Studies in various dijet topologies

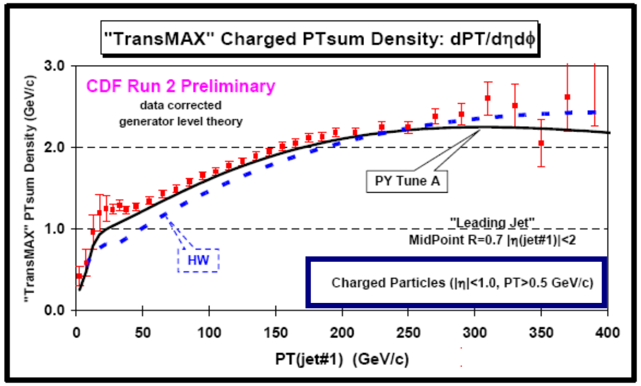
<u>Drell-Yan production:</u>

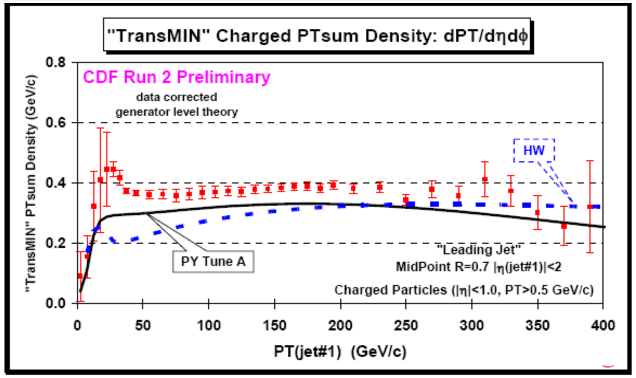
- Transverse and toward regions (excluding lepton-pairs) sensitive to UE
- Cleaner environment (Z/γ* carries no color)
- Limited statistics

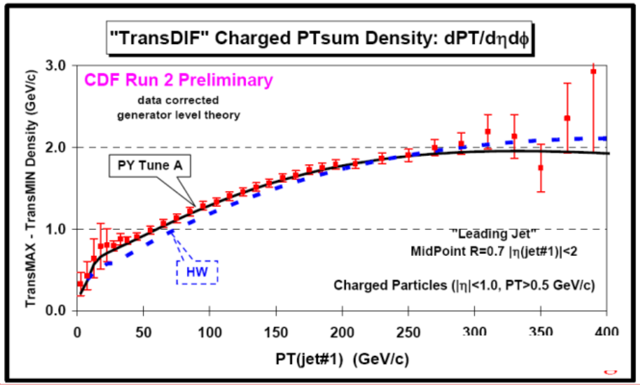
Underlying Event in Jet Events



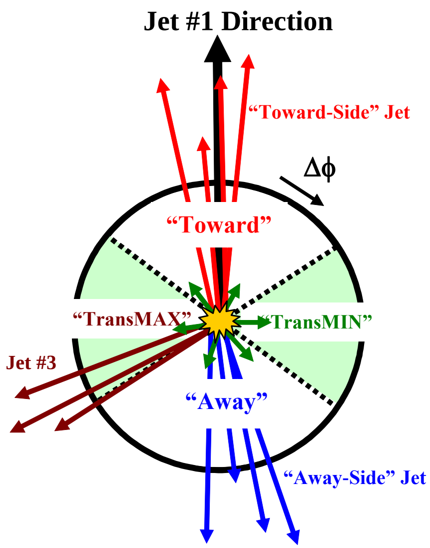
- Charged tracks with Pt>0.5 GeV & $|\eta|<1$
- Tuned PYTHIA (Tune A) doing "ok" generally
- TransMAX: "soft" and "semi-hard" components
- TransMIN: dominated by "soft" component
- TransDIF = TransMAX-TransMIN : sensitive to the semi-hard component of UE. Well described by Tuned PYTHIA (w/ multiple parton interactions)

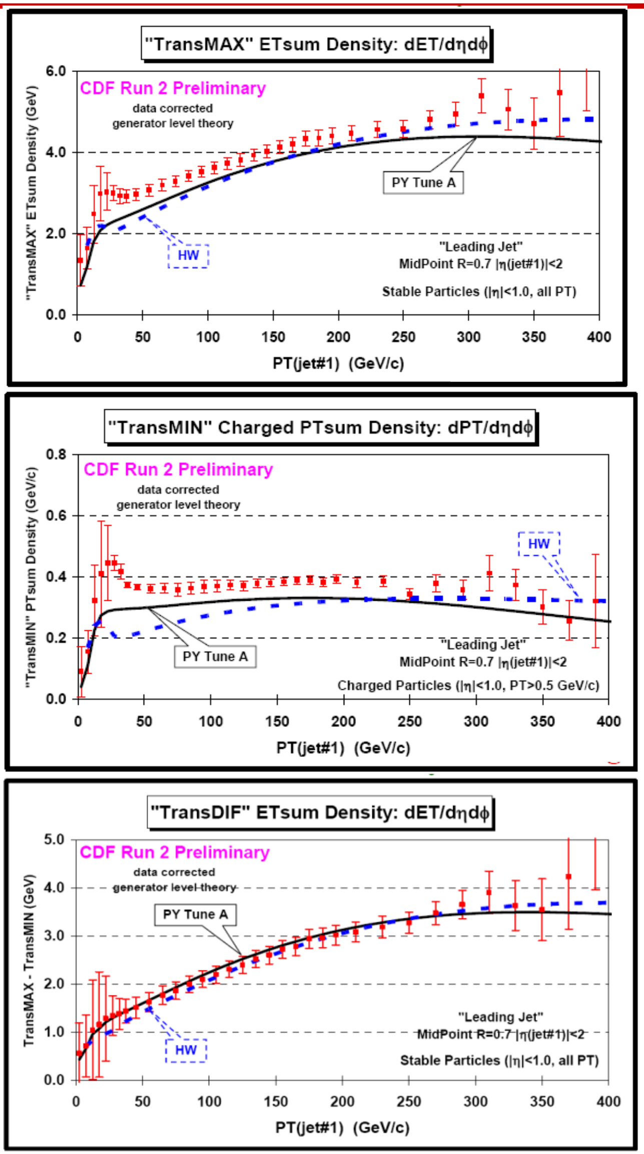






Underlying Event in Jet Events



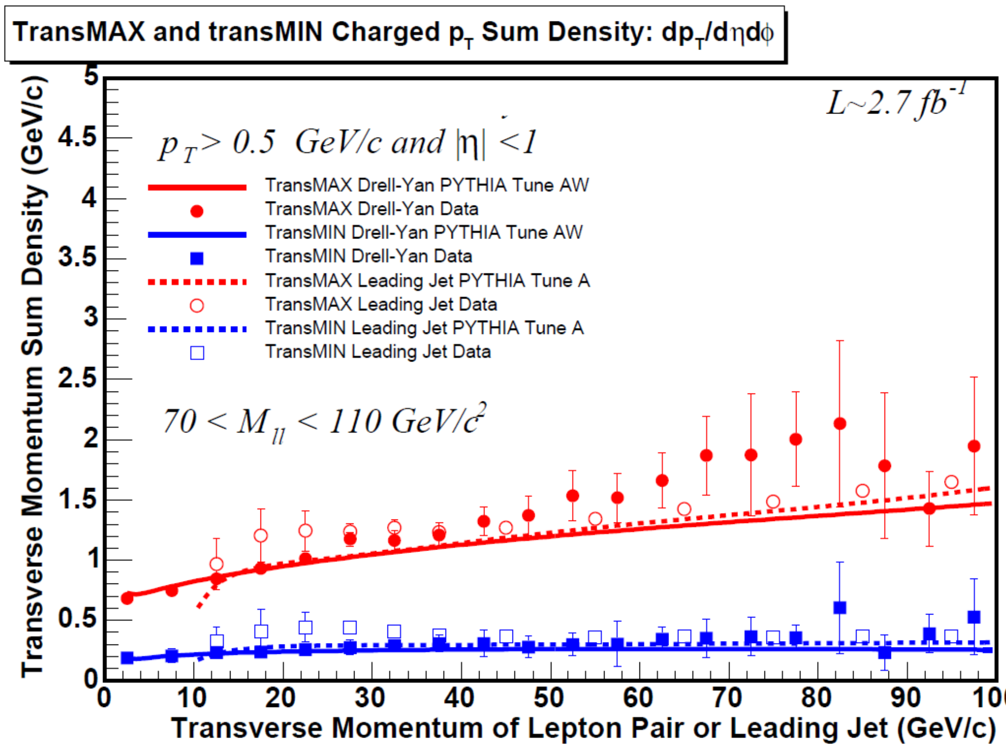


- Now, looking at all particles including neutrals (instead of charged particles only with p_T>0.5 GeV/c)
- Similar trend observed

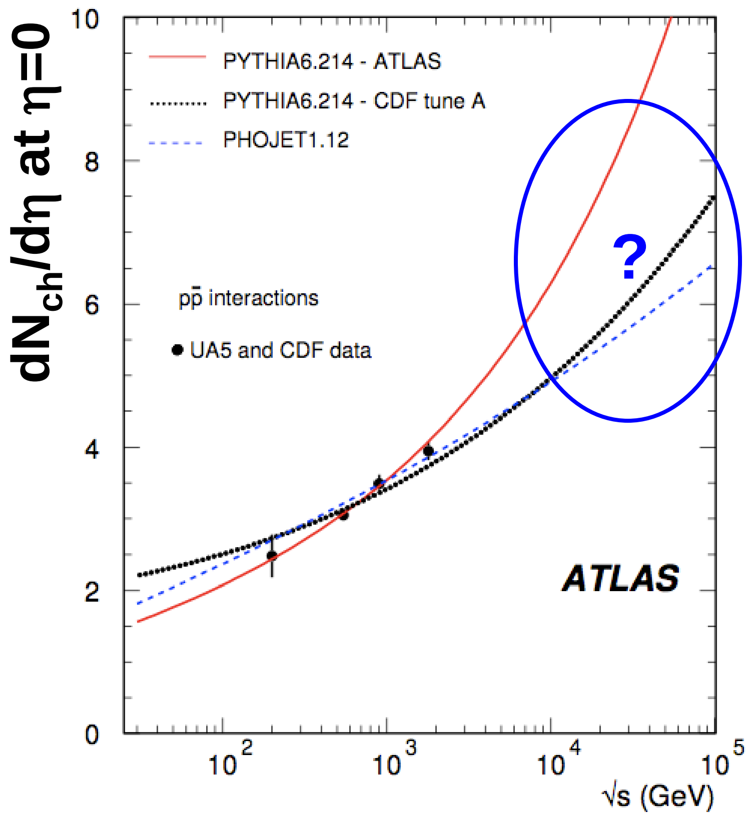
UE in DY and Jet Production

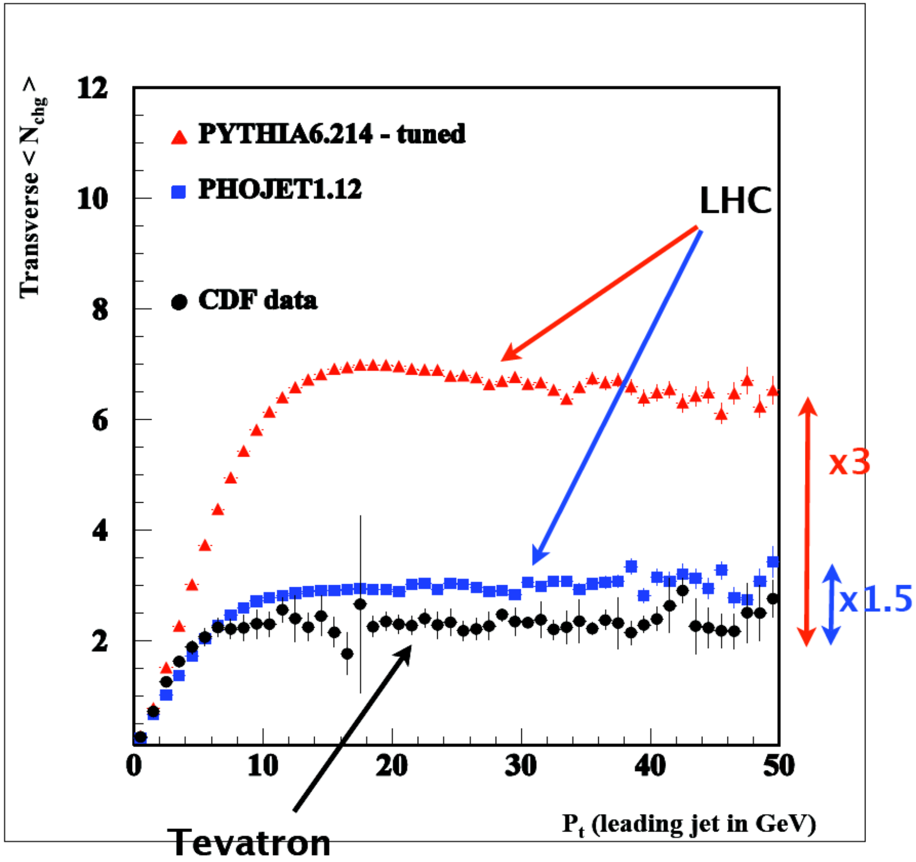
Comparisons between jet and Drell-Yan production:

- Similar trend in jet and DY events: UE universality!
- Tuned Pythia describe data reasonably well.



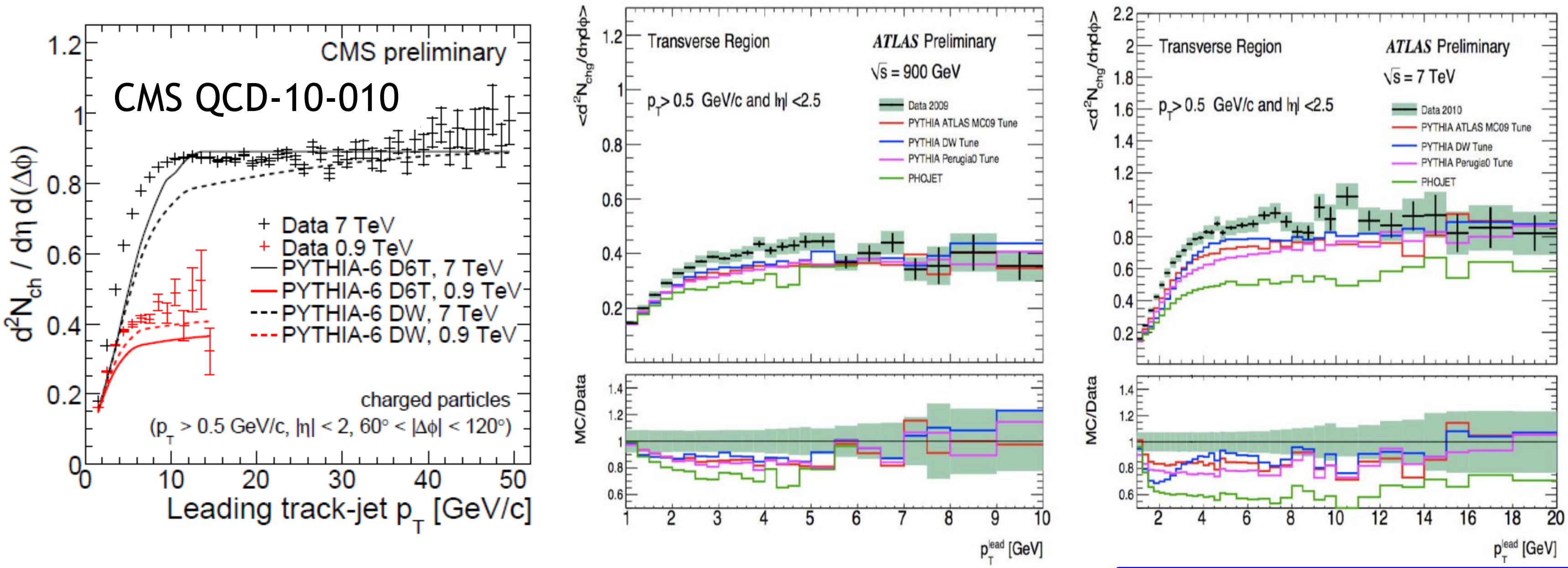
Underlying Event: Tevatron → LHC





- Extrapolation to the LHC energy has been rather ambiguous
  - Large model dependence on LHC predictions from Tevatron data
  - PYTHIA models favour $\ln^2(s)$; PHOJET suggests a $\ln(s)$ dependence.

Results from the LHC

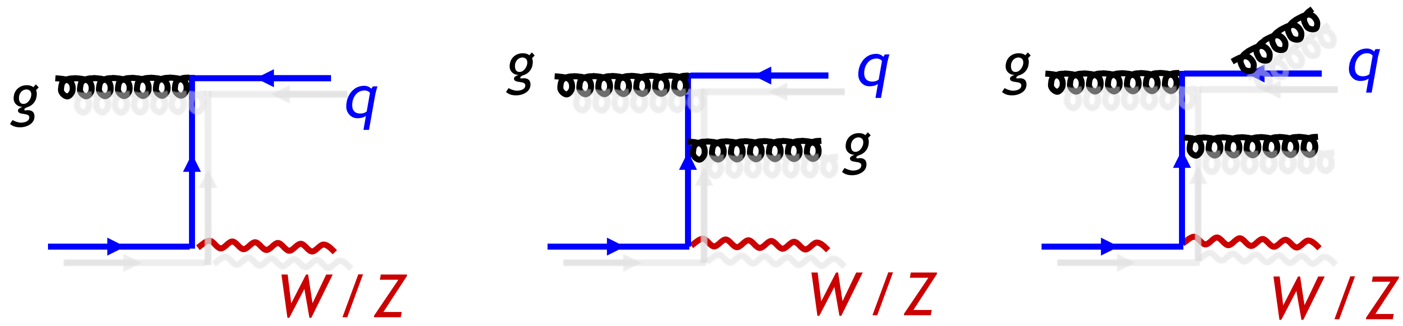


See lecture by J. Grosse-Oetringhaus

- New results are becoming available from the LHC
- Pythia tunes describe the gross features of the data but often fail in details
- Phojet MC underestimates the UE at 7 TeV
- The LHC measurements as well as Tevatron and RHIC measurements will help in understanding the properties of UE and multiple parton interactions

W/Z + Jets

W/Z+Jets Production



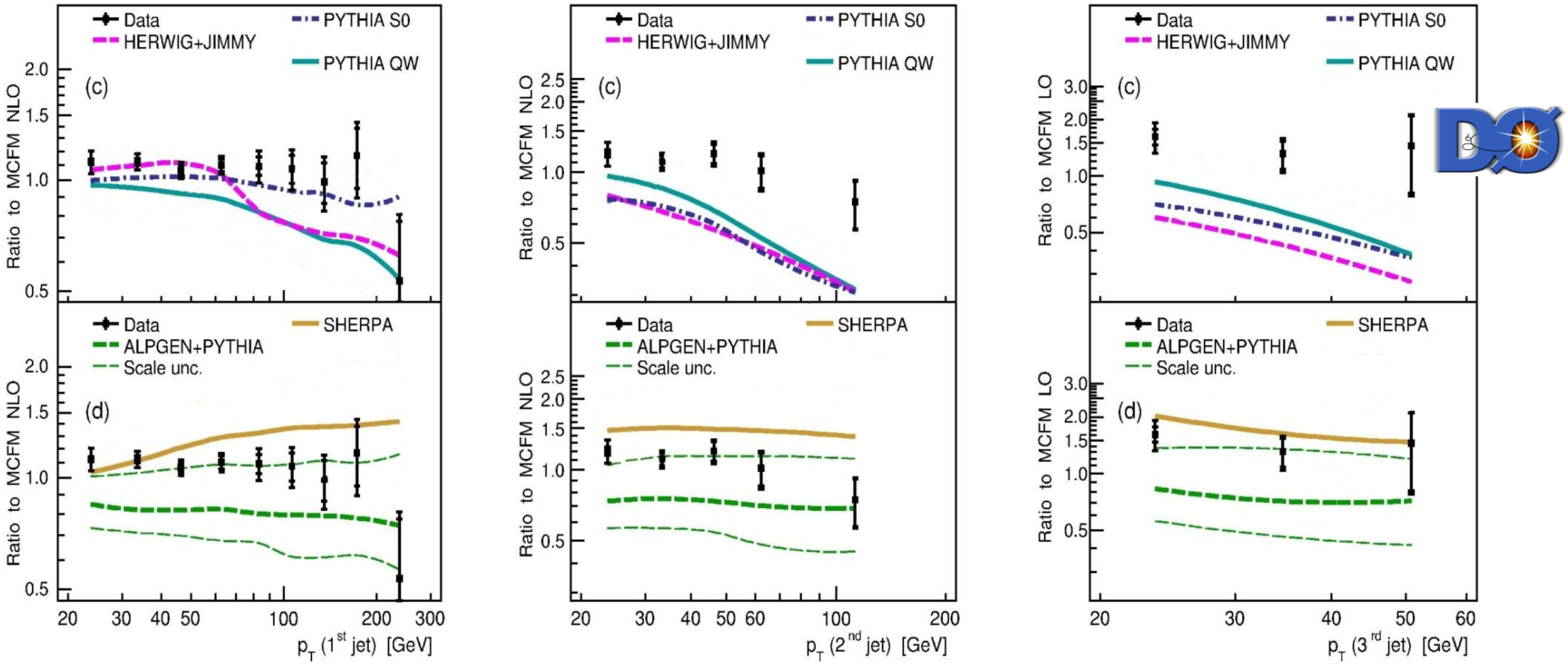
- W/Z+jets are critical for physics at the Tevatron and LHC: top, Higgs, SUSY, and other BSM
- NLO pQCD calculations are available up to >=2(3) jets
- Many Monte Carlo tools are available
  - LO + Parton shower Monte Carlo (Pythia, Herwig,)
  - Matched tree level matrix element + parton shower Monte Carlo (Alpgen, Sharpa,)
- These calculations and tools need “validation” by experimental measurements

Z + (1, 2, 3) Jets

See lecture by J. Owen

Testing Monte Carlo Models: favor Alpgen with low scale

Leading jet in Z + jet + X — Second jet in Z + 2jet + X — Third jet in Z + 3jet + X



Phys. Lett. B 669, 278 (2008), arXiv:0903.1748, arXiv:0907.4286

See also W+jets, CDF, Phys. Rev. D 77, 011108(R).

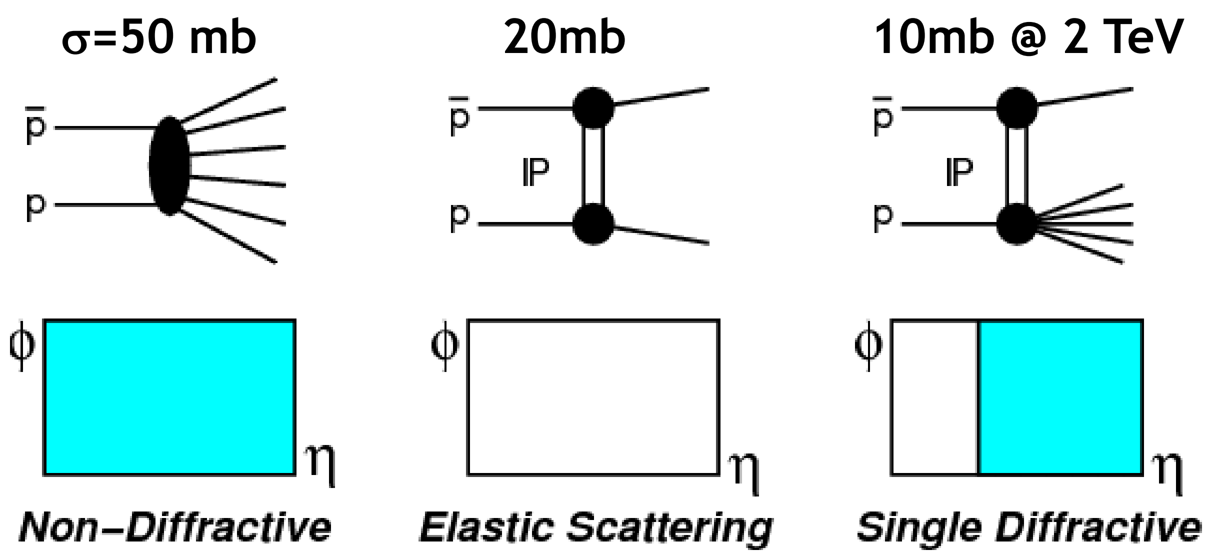
Diffractive Dijet and Exclusive Dijet Production

Diffractive Scattering

- We usually study so-called non-diffractive events, in which both incoming hadrons break up.
- In a significant fraction pp(bar) events, both hadrons (elastic) or one hadron (diffractive) stays intact (escape in beampipe)
- Cannot apply perturbation theory (no hard scale)
- Study diffractive events containing high Pt jets (diffractive jets)

IP: pomeron (vacuum quantum number)

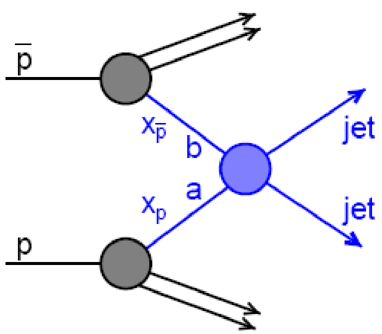
Shaded Area : Region of Particle Production



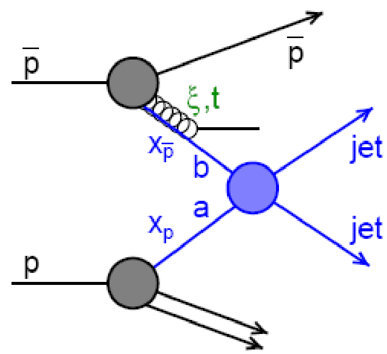
Diffractive Dijet Production

- Use high Pt jets as a probe to determine the partonic structure of the diffractive exchange (F^D_{jj})

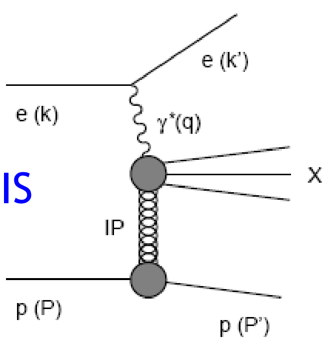
Non-diffractive dijet



Diffractive dijet



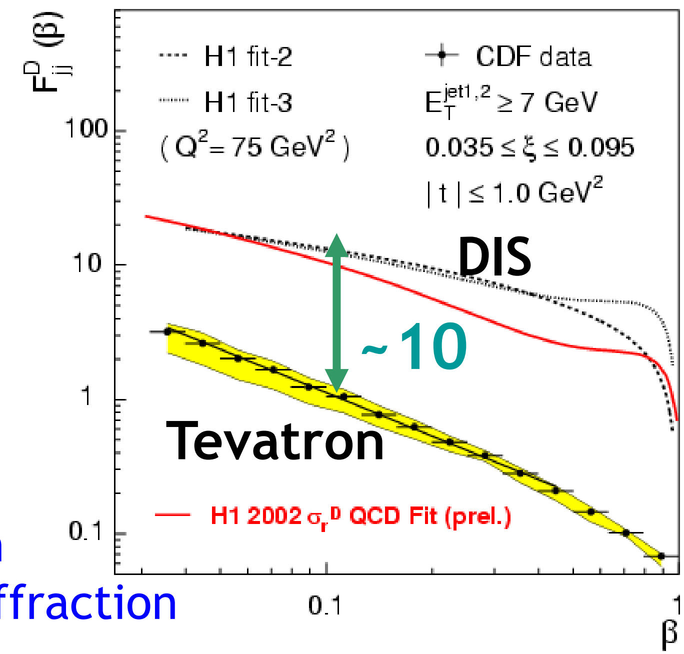
Diffractive DIS



- Diffractive dijet cross section

$$\sigma(\bar{p}p \to \bar{p}X) \approx F_{jj} \otimes F^D_{jj} \otimes \hat{\sigma}(\to jj)$$

- Compare with diffractive PDF from diffractive DIS

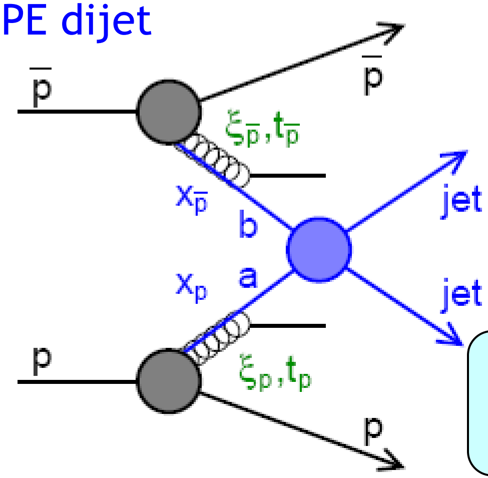


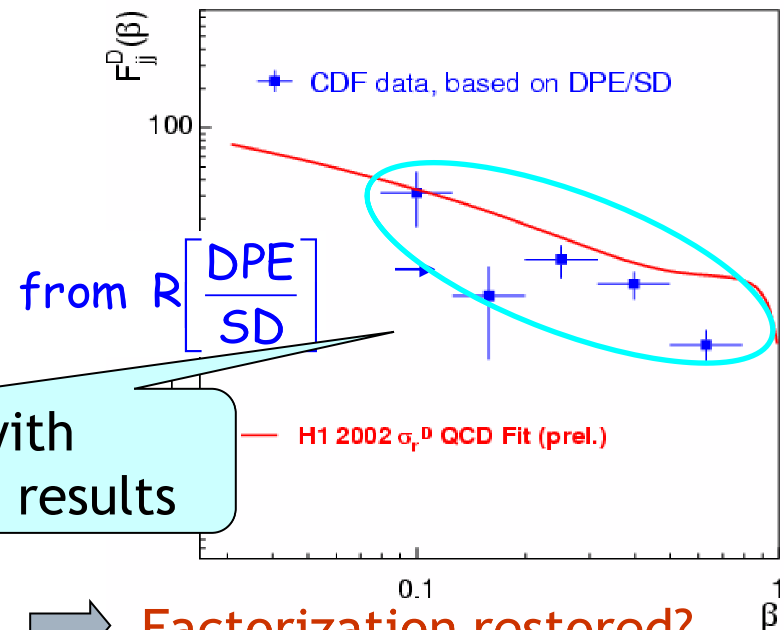
Diffractive PDF not universal:
QCD factorization breakdown for diffraction

Diffractive Structure Function

- Measure F^D_{jj} in double pomeron exchange (DPE) dijet production (both p and pbar stay intact)

DPE dijet





~ Consistent with diffractive DIS results

⇨ Factorization restored?

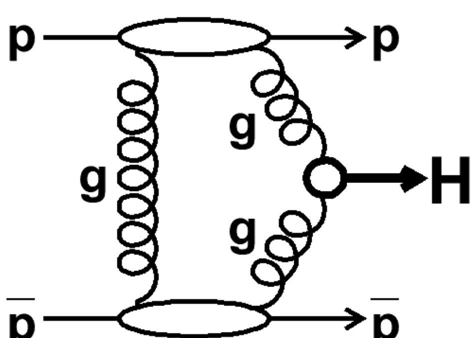
- Single diffractive dijet is suppressed (factor~10) in hadron-hadron collisions, but double pomeron process has no “extra” suppression
- Fit to “rapidity gap survival probability” models
  - Suppression due to soft particle re-scattering spoil the diffractive signature

Exclusive Higgs / Dijet Production

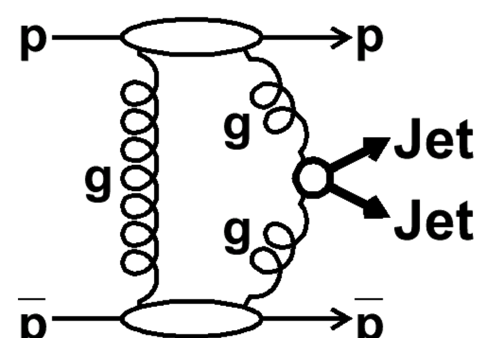
- Exclusive Higgs production?
  - Event consists of nothing but leading protons and Higgs
  - Will allow accurate Higgs properties from protons @ LHC

- Exclusive Higgs production too rate at the Tevatron, but can test/calibrate exclusive production model with dijet production

Exclusive Higgs



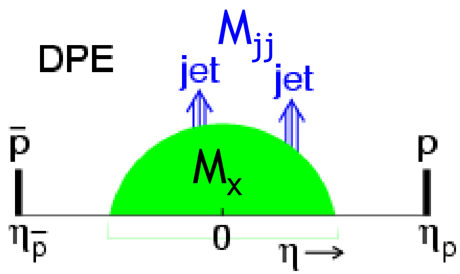
Exclusive Dijet

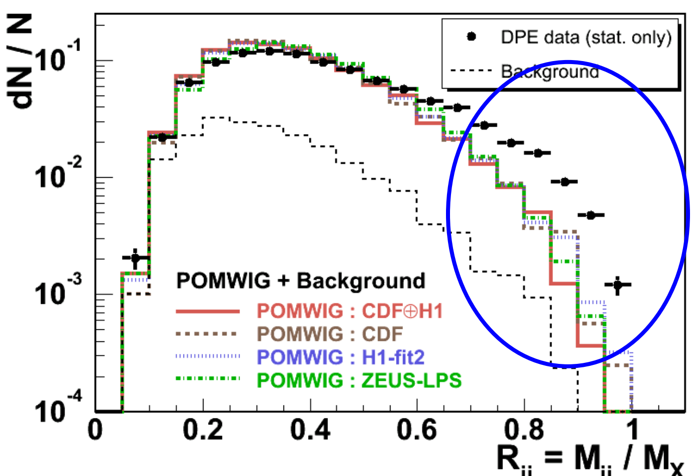


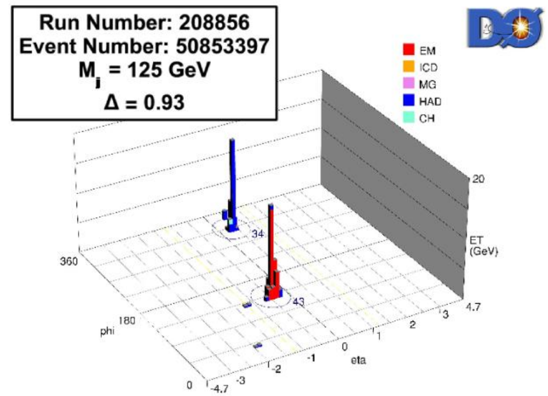
Observation of Exclusive Dijet

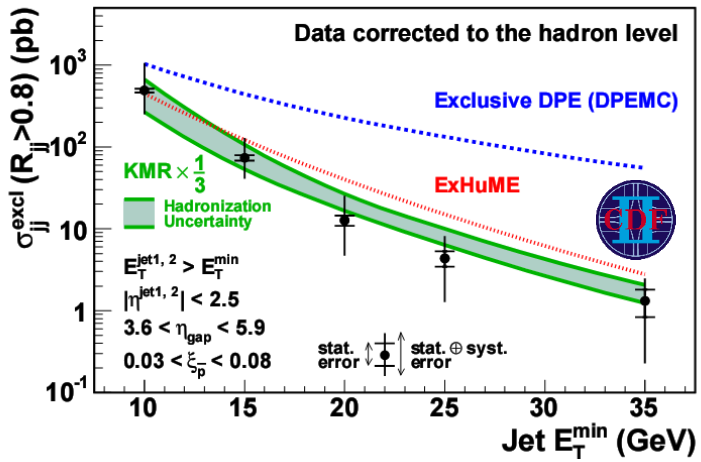
- Search strategy:
  - Reconstruct dijet mass fraction :

    $R_{jj} = M_{jj} / M_X$
  - Look for enhancement at high $R_{jj} \sim 1$









CDF, PRD 77, 052004 (2008)
Also DØ Note 6042-CONF (2010)

Observation of Exclusive Dijet

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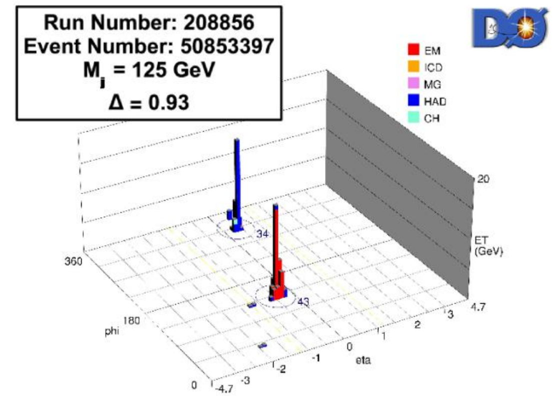
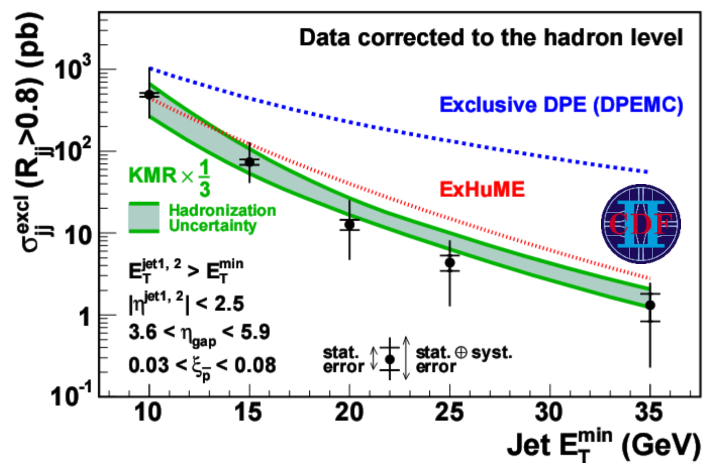


At the LHC:

- Expected SM exclusive Higgs cross section is ~ 3fb (much higher in certain MSSM scenarios)
- The forward proton detectors (FP420/HPS/AFP) have been proposed/planned to explore this channel
- Can allow accurate mass determination and spin.

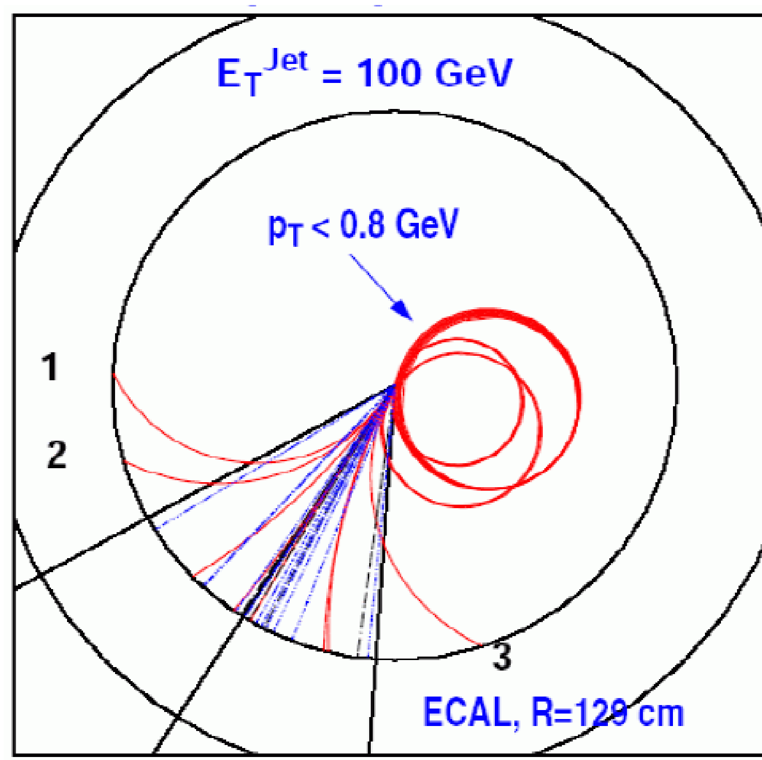


CDF, PRD 77, 052004 (2008)
Also DØ Note 6042-CONF (2010)

More News on Jets from the LHC

Jet Plus Track (JPT) Jets

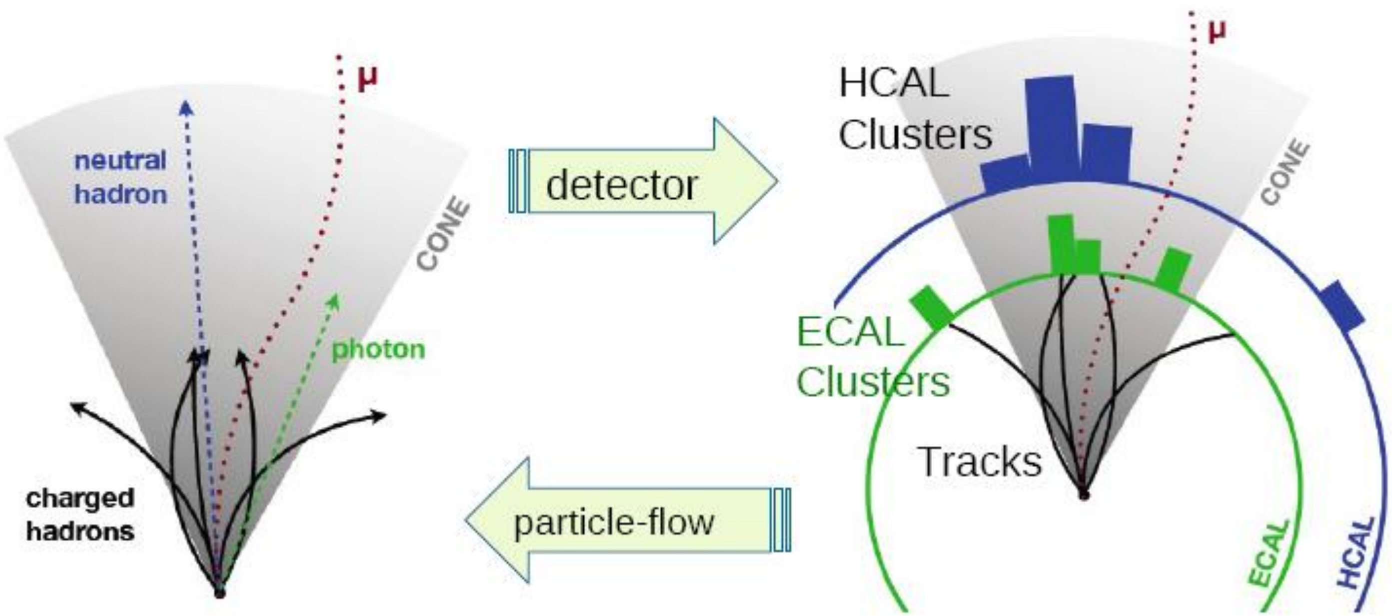
- Jets have been primarily measured by the calorimeters
- Main idea: Improve using tracks
  - Tracking system measure charged hadrons better than calorimeter (in-calo-cone tracks)
  - Recover also charged hadrons leaking outside the jet area (out-of-calo-cone tracks)
  - Similar techniques in OPAL, H1, CDF, …



- Algorithm:
  - Subtract average expected response of in-calo-cone tracks from calorimeter measurement and add tracks
  - Add momentum of “out-of-cone” tracks

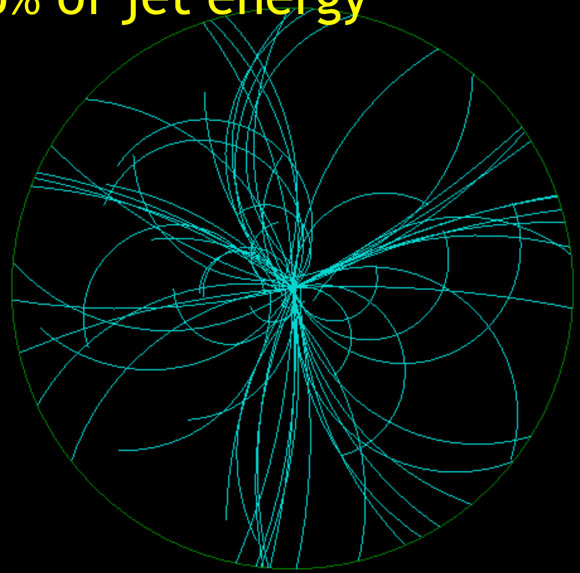
Particle Flow (PF) Algorithm

- Basic idea:
  - Reconstruct and identify all different types of particles
  - Apply corresponding calibrations
  - The list of “particles” is given to the jet clustering algorithm



Particle Flow Algorithm

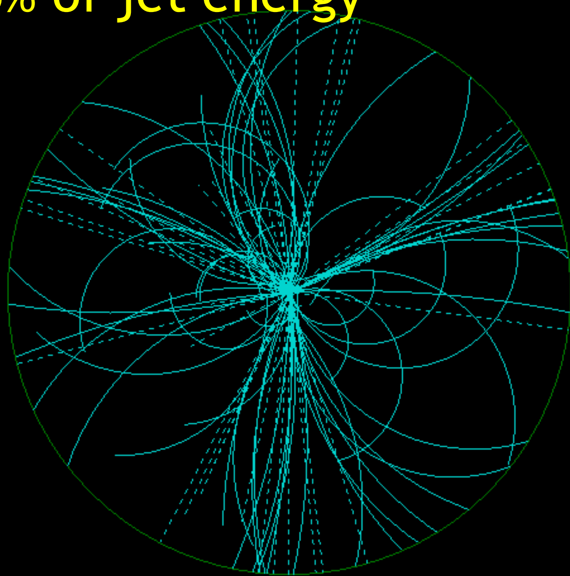
Charged hadrons
~65% of jet energy



Use the high resolution tracker
~1% at 100 GeV

Particle Flow Algorithm

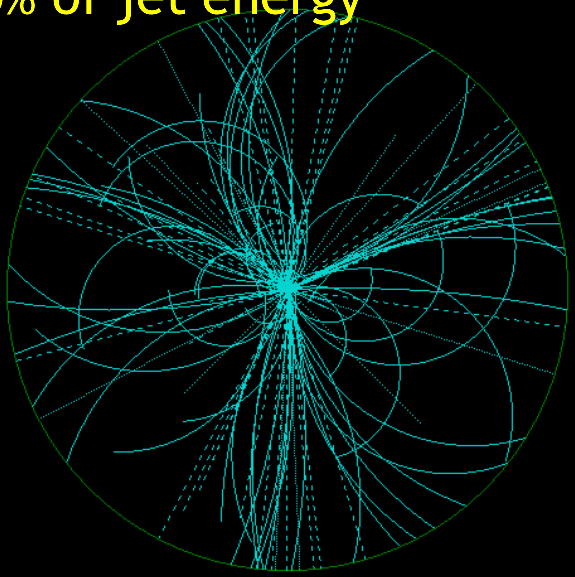
Photons
~25% of jet energy



Use high resolution / good granularity ECAL
Granularity: 0.02 ($\Delta\eta\times\Delta\varphi$)
Energy resol: ~2%/$\sqrt{E}$

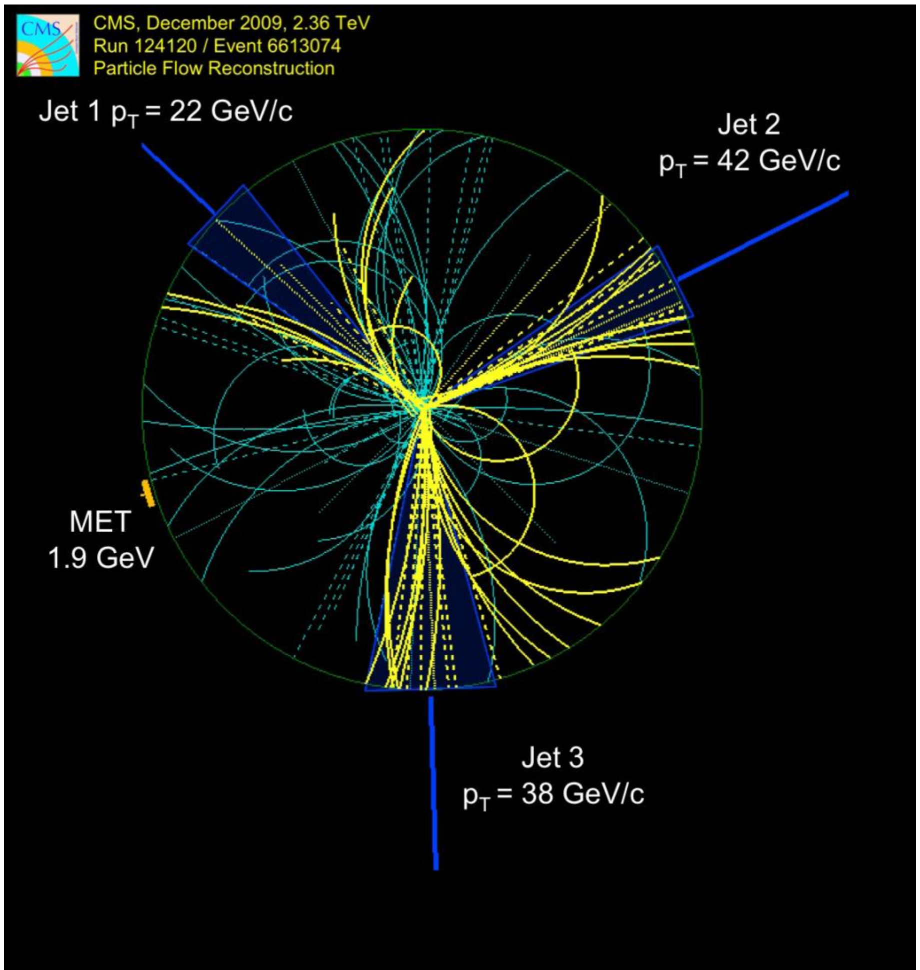
Particle Flow Algorithm

Neutral hadrons
~10% of jet energy



Use HCAL
Granularity: 0.1 ($\Delta\eta\times\Delta\varphi$)
Energy resol: ~100%/$\sqrt{E}$

Particle Flow Algorithm



Particles clustered in jets

Jet

Charged hadron (solid)

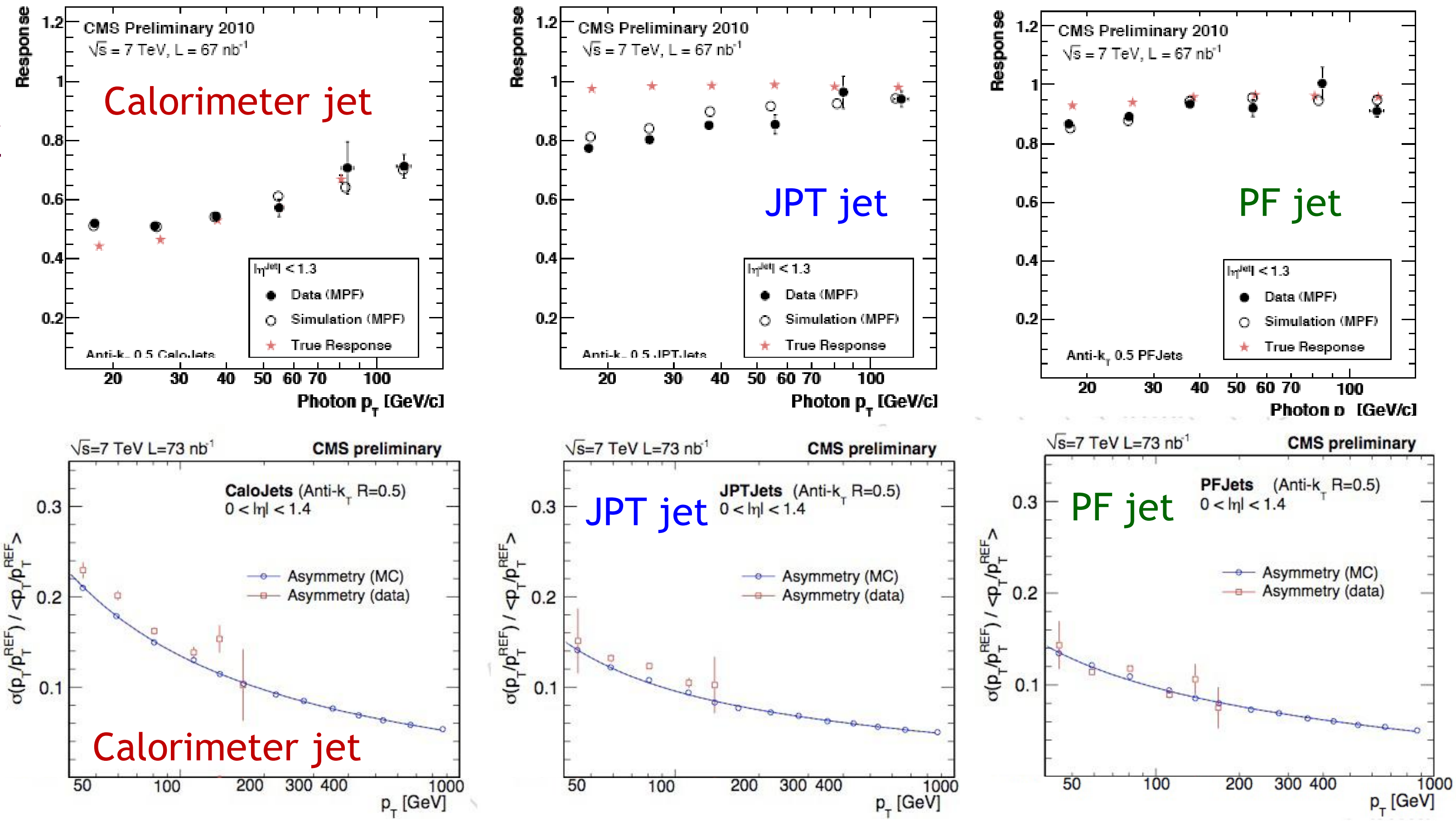
Photon (dashed line)

Neutral hadron (dotted line)

JPT and PF Jets Performance

Jet energy response

Jet energy resolution



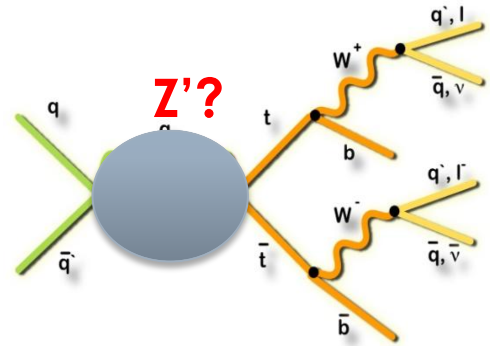
- JPT jets and especially PF jets improve both jet response and resolution significantly

Jet Substructure in Higgs & New Physics Searches

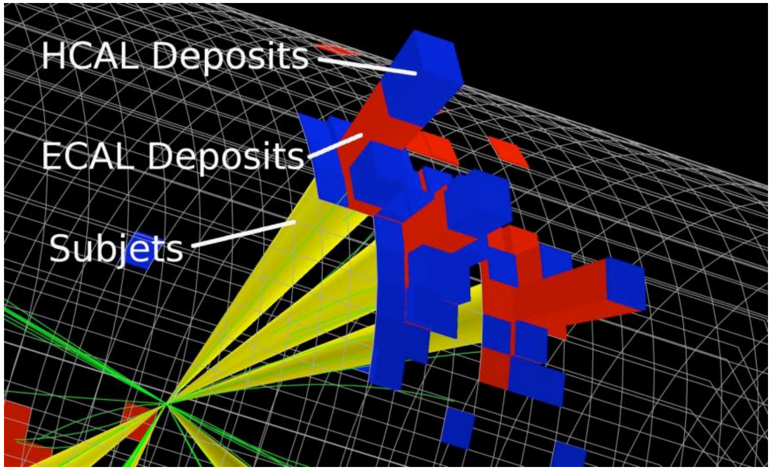
- Basic idea: At LHC, even $\sim m_{EW}$ or $>m_{EW}$ particles are often highly boosted, and they produce a single massive jet. Identify them by looking at subjets.

- Discussed in many literatures:
  - Z. Phys. C62 (1994) 127; Seymour
  - Comput.Phys.Commun.153(2003)85; Butterworth, Cox, Forshaw
  - arXiv:0802.2470; Butterworth, Davison, Rubin, Salam
  - arXiv:0806.0023; Thaler and Wang
  - arXiv:0806.0848; Kaplan, Rehermann, Schwartz, Tweedie
  - arXiv: 0903.5081; Ellis, Vermilion, Walsh
  - and many others

New Physics Search in Boosted Top-Jets



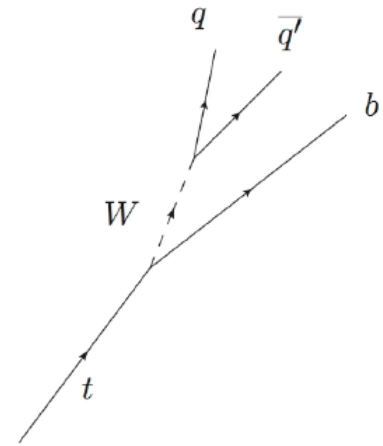
- TTbar resonances often appears in BSM models (Randall-Sundrum Kaluza-Klein gluons, Z', etc)
- Top quark has the largest branching fraction in all hadronic channel (46%)
- If the new particle is heavy, "boosted" tops will create a single jet → dijet events
- Can we detect them? How can we suppress the huge QCD BG?
  - Discriminate top from non-top based on subjets
  - Use # of subjets, top mass (3-jet mass) & W mass (2-jet mass) as discriminant

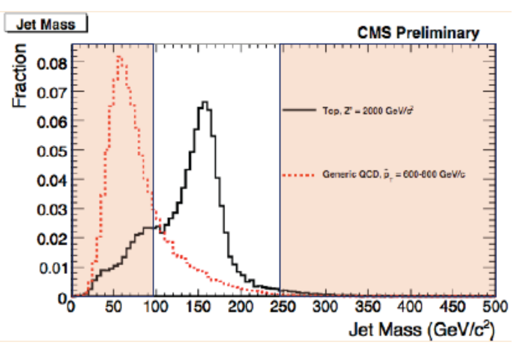


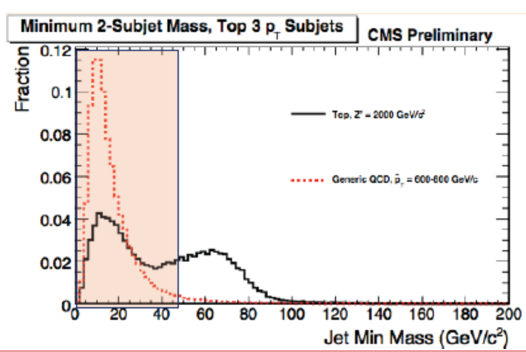
arXiv:0806.0848; Kaplan, Rehermann, Schwartz, Tweedie, CMS EXO-09-002

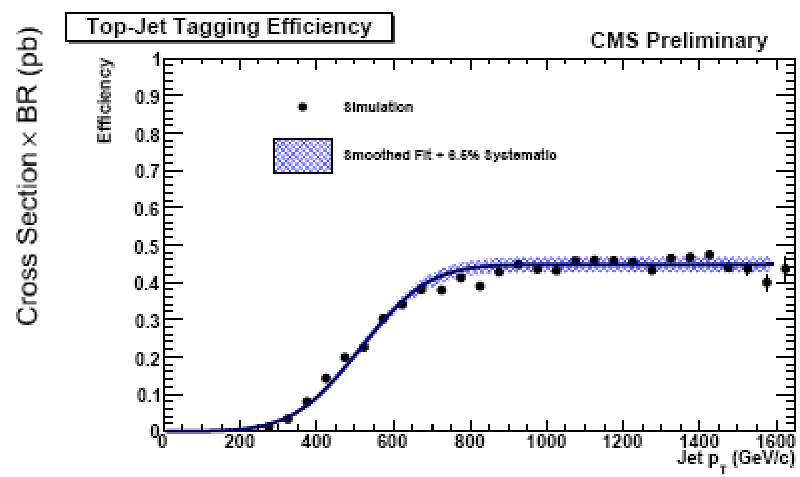
New Physics Search in Boosted Top-Jets

- Procedure:
  - Find “hard jets” with the Cambridge-Aachen algorithm (R=0.8, Pt>250 GeV, |y|<2.5)
  - Reverse the clustering sequence
    - throw out soft cluster (Pt fraction<0.05). CA algo is favorable in this step.
  - Find 3 or 4 hard subjets? Take highest 3 subjets.
  - Subjet masses? (without b-tagging information)
  - Efficiency 46% for Pt>0.6-0.7 TeV
  - With ~200 pb-1, start to be sensitive realistic BSM scenarios



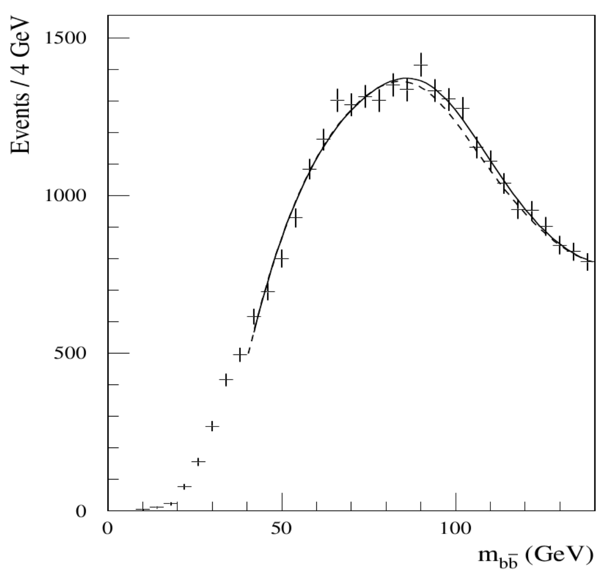


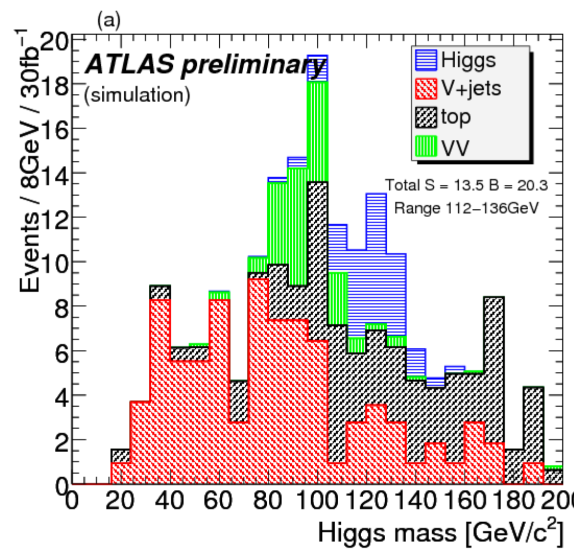




Boosted Higgs

- Higgs search in the WH channel, which is most sensitive channel for low mass Higgs at the Tevatron, “has been” considered challenging at the LHC.
  - Overwhelming W/Z background → Little sensitivity (S/B~1%)
- Working with boosted Higgs brought a hope to this channel (H and W/Z Pt>200 GeV)
- In contrast to the boosted top case, b-tagging is critical. Need a good b-tagging in the boosted environment





arXiv:0802.2470 ATL-PHYS-PUB-2009-088

Summary & Remarks

- Jet results at the Tevatron have reached high precision, and provided critical information on
  - PDF
  - α_s
  - Monte Carlo tunings

  All Tevatron experience benefits LHC physics

- LHC started to deliver physics results with jets
  - **Rich QCD program planned at LHC has just started**

- Jets play important roles in Higgs and new searches both as a part of signal and as an important background to be understood
  - New physics might be around the corner !

Acknowledgement

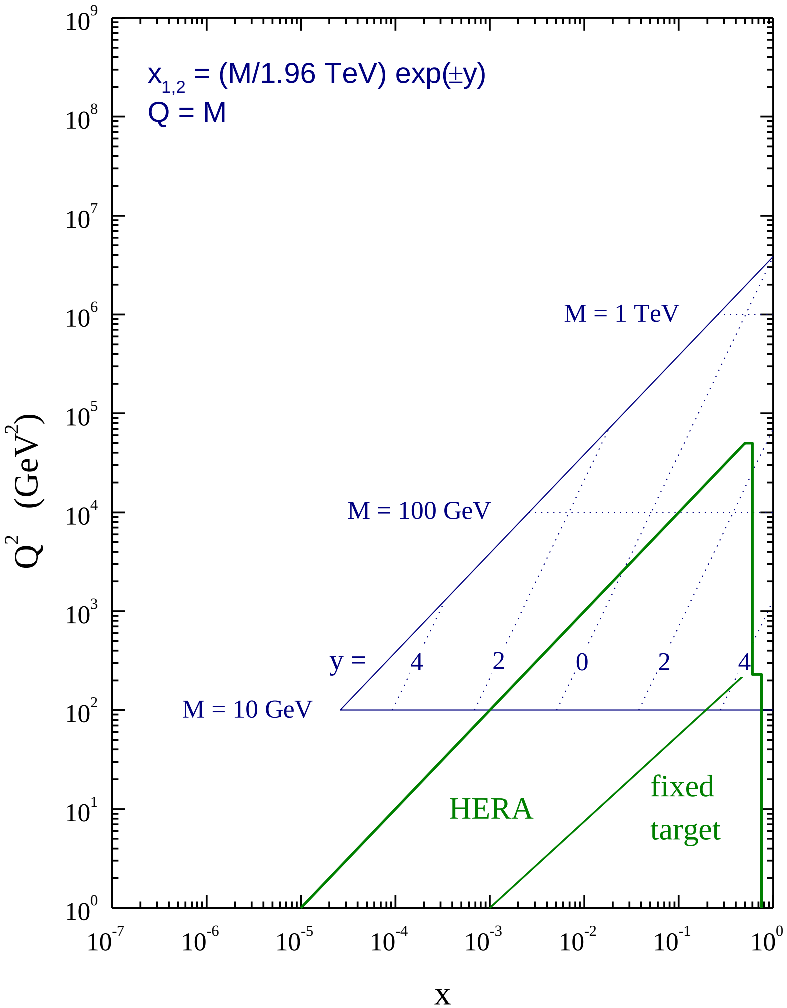
- Many thanks to:

  N. Valeras, B. Gary, M. Zielinski, C. Glasman, J. Houston, S. Rapoccio, F. Beaudette, A. Bhatti, Ia Iashivili, A. Korytov, G. Salam, M. Seymour, M. Albrow and others

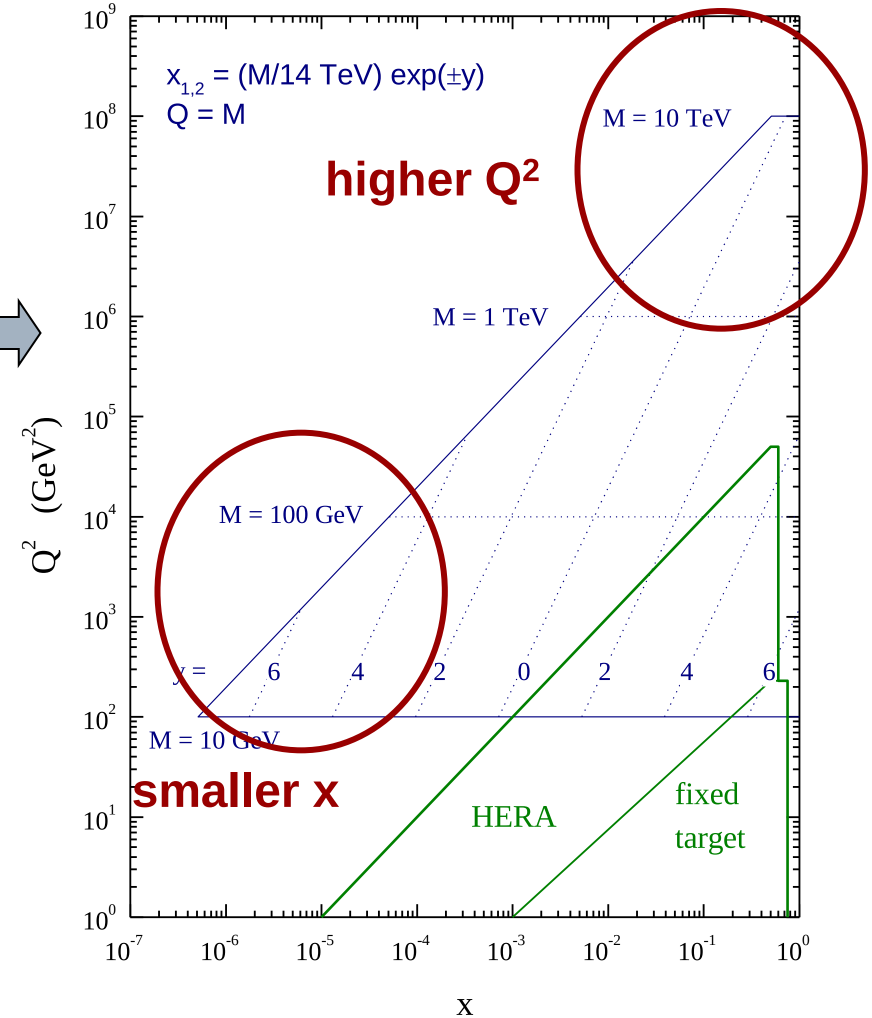
Backup

Tevatron → LHC Parton Kinematics

Tevatron

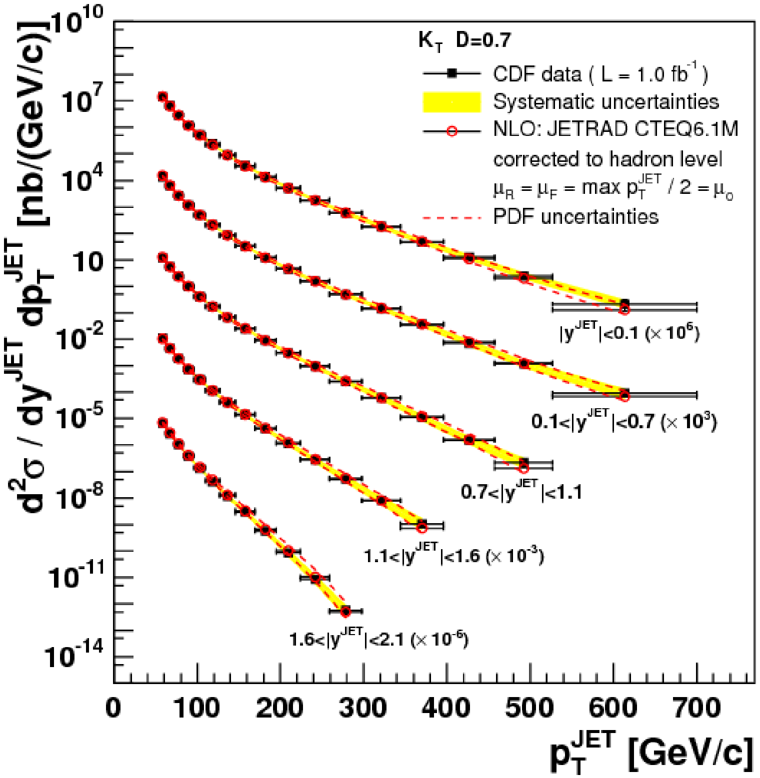


LHC

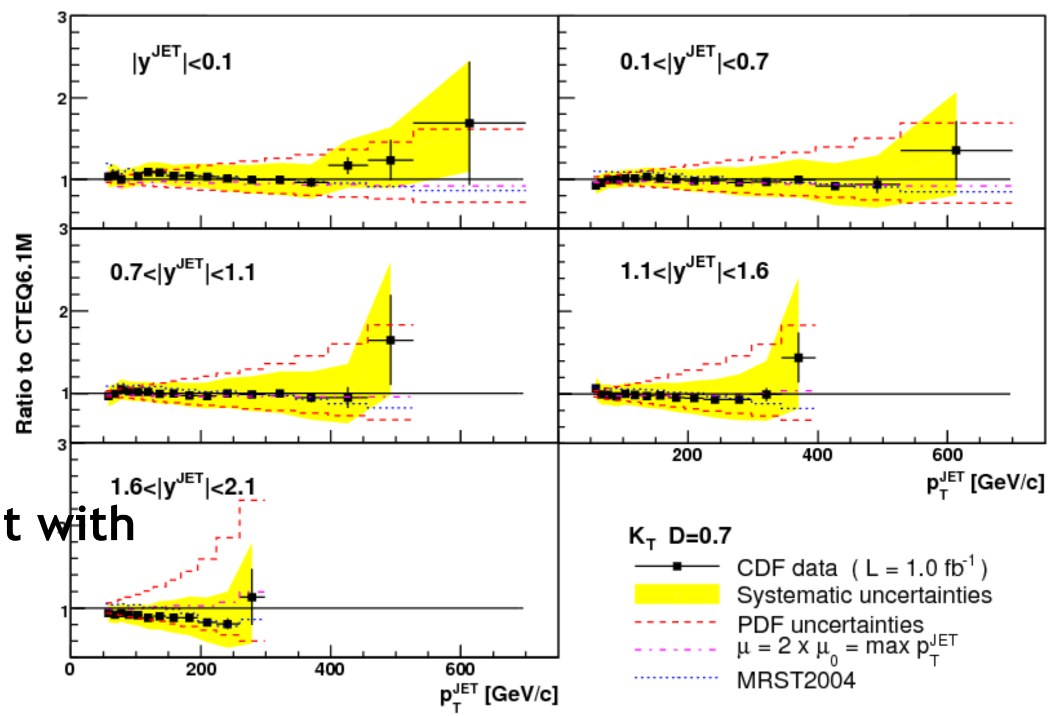


From J. Stirling (U. Durham)

Inclusive Jets with k_T Algorithm



- $L = 1.0\ fb^{-1}$
- Jets reconstructed with the k_T algorithm, *D*= 0.7.

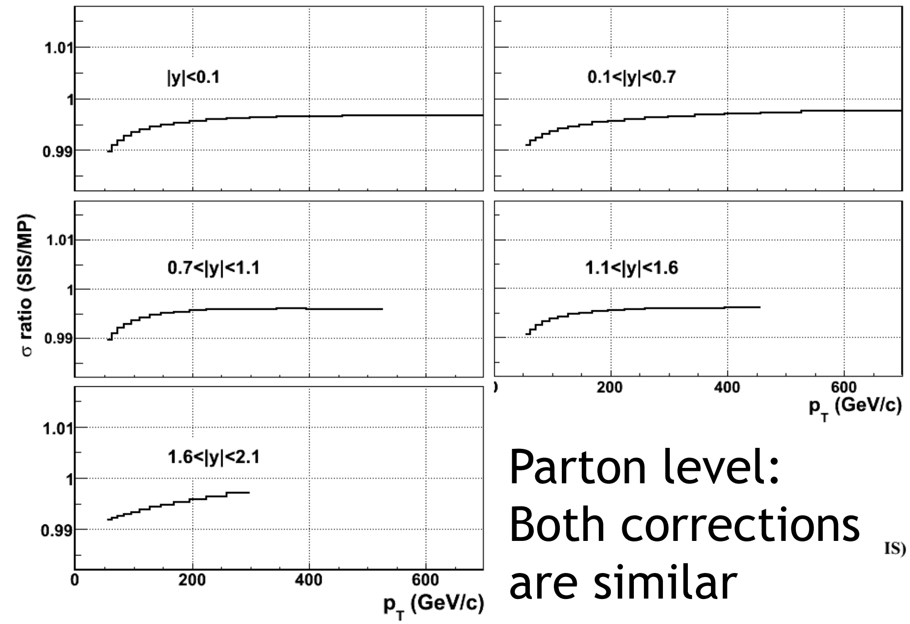


Again, data in good agreement with NLO pQCD predictions

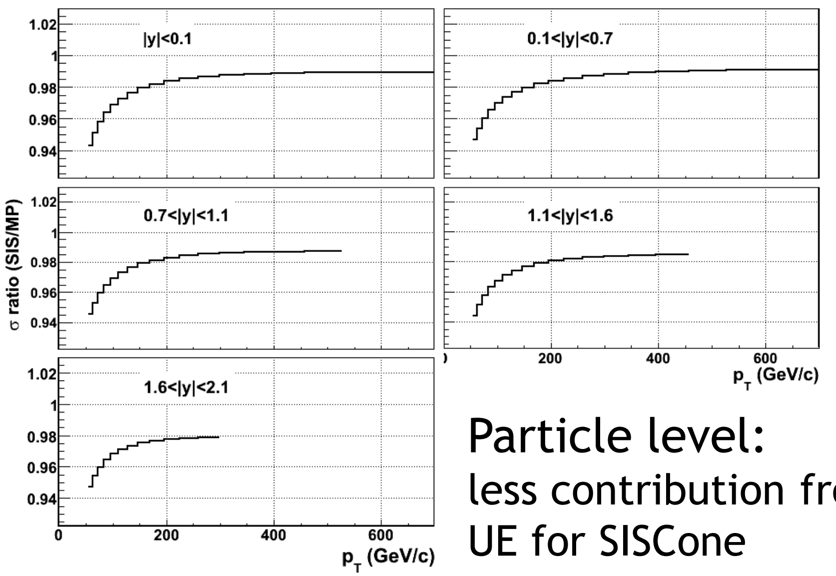
Phys. Rev. D 75, 092006 (2007)

SISCone Vs Midpoint

- SISCone is preferred theoretically due to infrared and collinear safety at all orders of pQCD (Midpoint only up to NNLO)



Parton level: Both corrections are similar



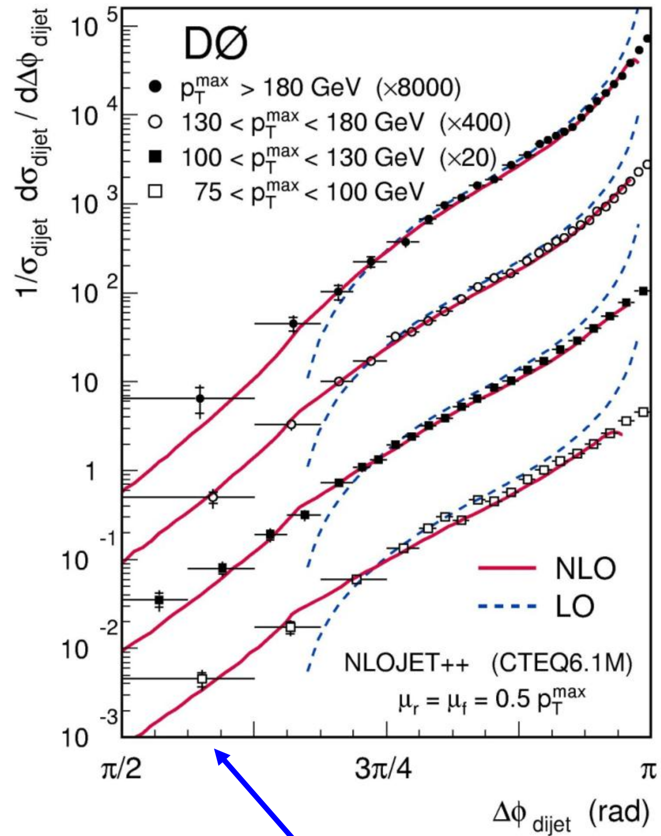
Particle level: less contribution from UE for SISCone

- No explicit jet cross section measurement with SISCone at the Tevatron, but a MC study was performed
- Differences of a few percent at the particle level reduces to ~1% at the parton level
- Negligible effect

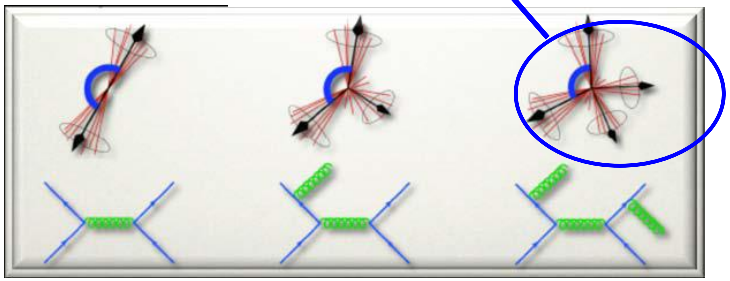
Dijet Angular Distribution

PRL. 94, 221801 (2005)

- Azimuthal angle between the two leading jets
  - Sensitive to higher order radiation w/o explicitly measuring radiated jets
- Shape Analysis: $\dfrac{1}{\sigma_{dijet}}\dfrac{d\sigma}{d\Delta\varphi}$
  - Less sensitive to theoretical (hadronization, underlying event) and experimental (JEC, luminosity) uncertainties



- Test of pQCD predictions
- Important for e.g. tuning MC parameters (ISR)



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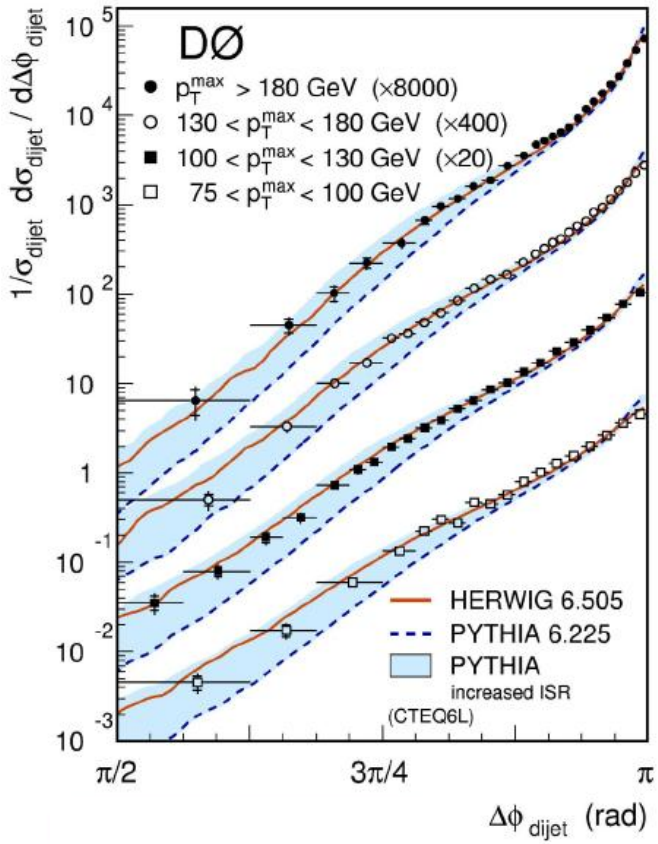

- Test of pQCD predictions
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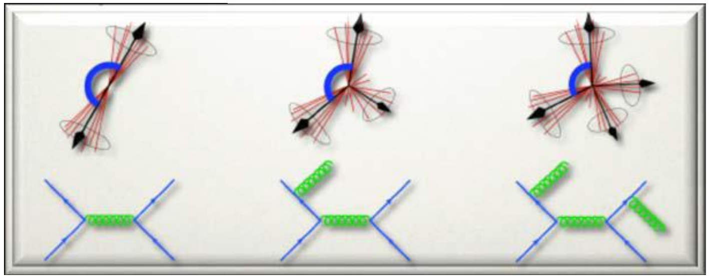
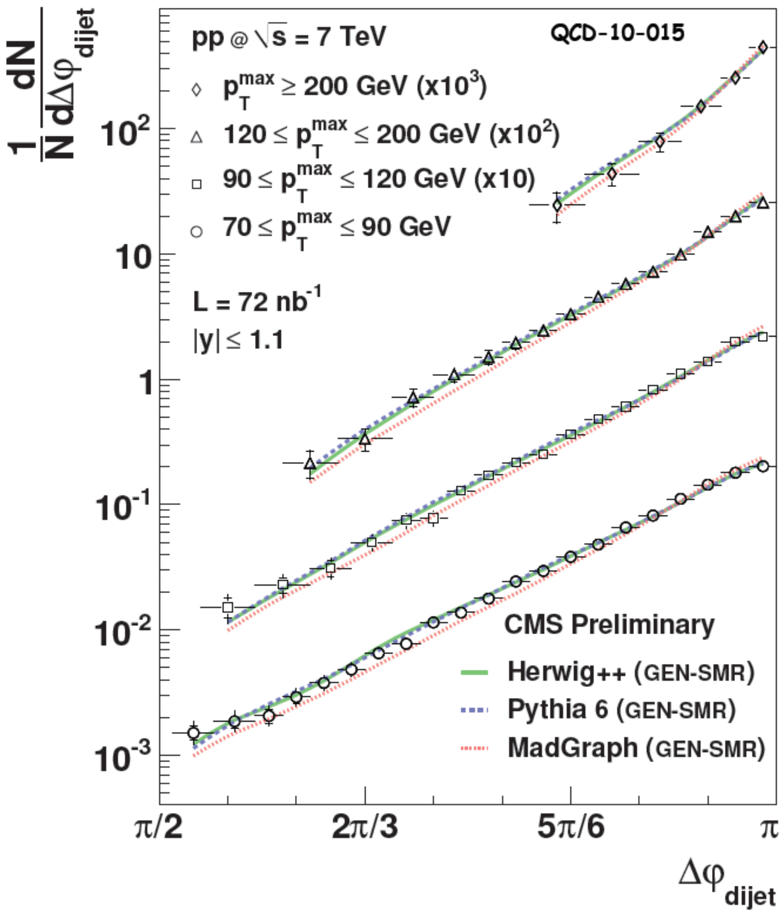
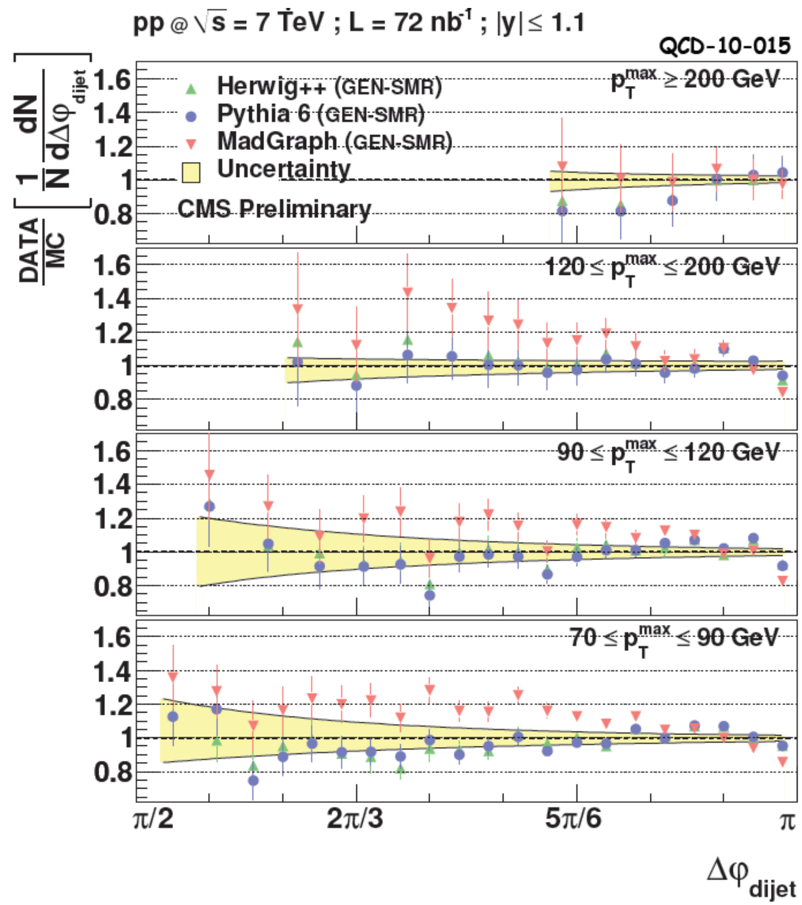


Results from the LHC

See lecture
by K. Rabbertz

CMS QCD-10-015





- Comparisons between preliminary data and different models show good agreement with Pythia & Herwig, but less agreement with MadGraph at low Pt

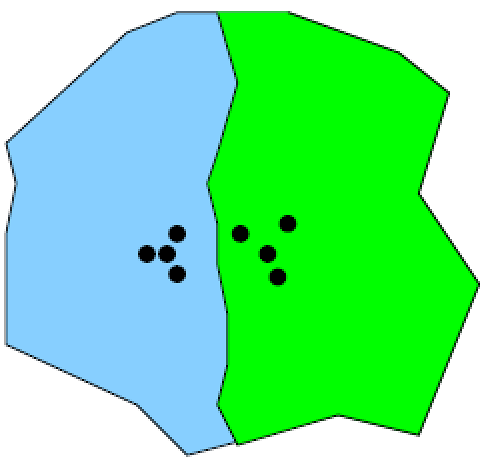
#1: Our tool

The Cambridge/Aachen jet alg. Dokshitzer et al '97
Wengler & Wobisch '98

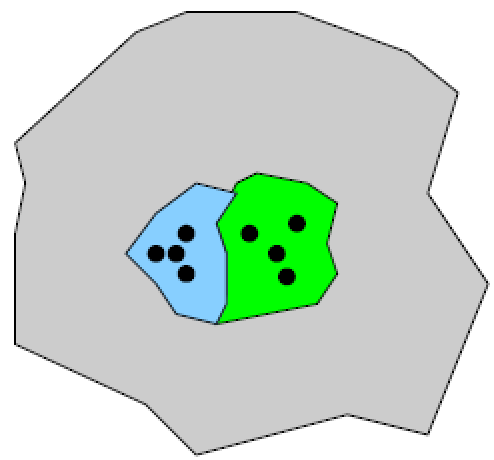
Work out $\Delta R_{ij}^2 = \Delta y_{ij}^2 + \Delta\phi_{ij}^2$ *between all pairs of objects* i, j*;*
Recombine the closest pair;
Repeat until all objects separated by $\Delta R_{ij} > R$. [in FastJet]

Gives "hierarchical" view of the event; work through it backwards to analyse jet

k_t algorithm

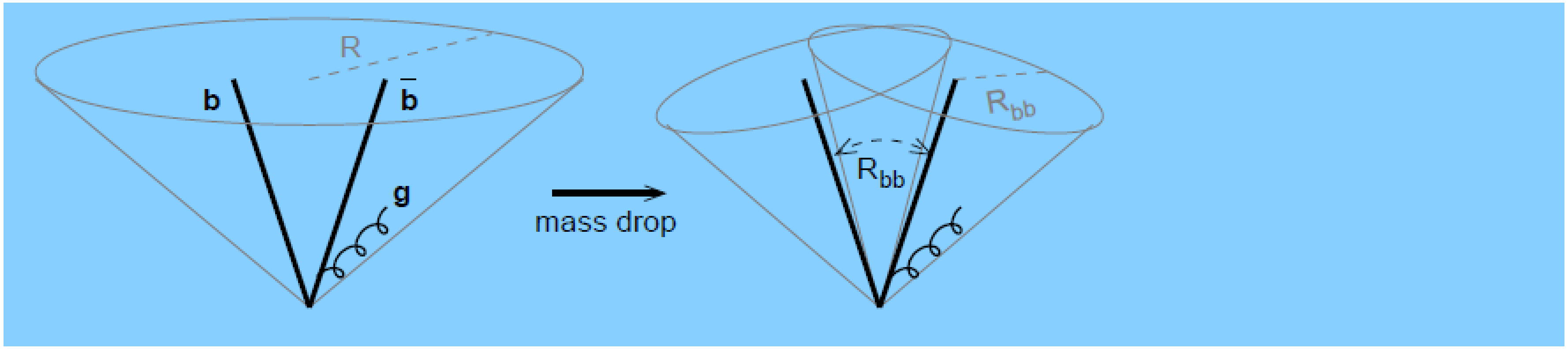


Cam/Aachen algorithm



Allows you to "dial" the correct R to keep perturbative radiation, but throw out UE

#2: The jet analysis



Start with high-p_t jet

1. Undo last stage of clustering ($\equiv$ reduce R): $J \to J_1, J_2$

2. If $\max(m_1, m_2) \lesssim 0.67m$, call this a **mass drop** [else goto 1]

   Automatically detects correct $R \sim R_{bb}$ to catch angular-ordered radn.

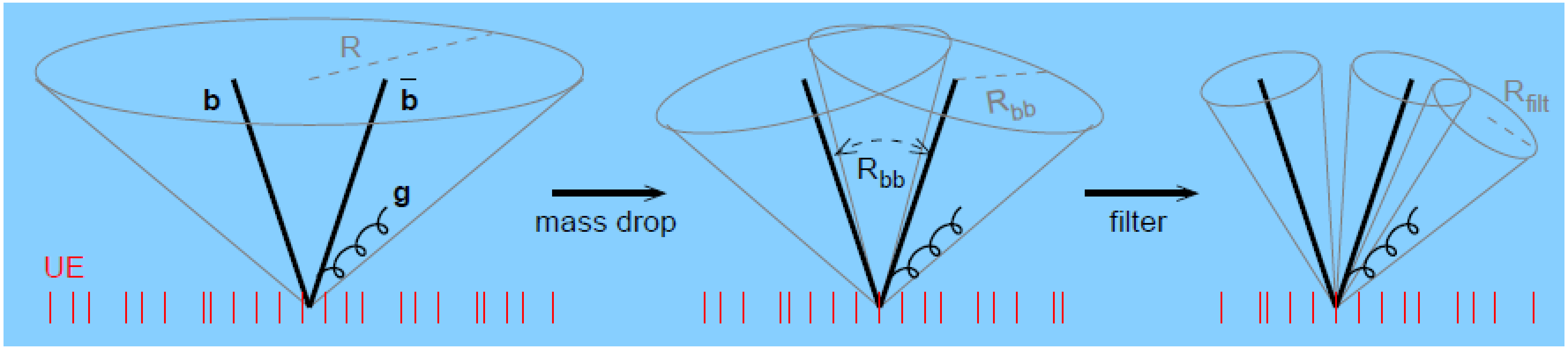
3. Require $y_{12} = \frac{\min(p_{t1}^2, p_{t2}^2)}{m_{12}^2} \Delta R_{12}^2 \simeq \frac{\min(z_1, z_2)}{\max(z_1, z_2)} > 0.09$ [else goto 1]

   dimensionless rejection of asymmetric QCD branching

4. Require each subjet to have b-tag [else reject event]

   Correlate flavour & momentum structure

#3: jet filtering



At moderate p_t, R_{bb} is quite large; *UE & pileup degrade mass resolution*

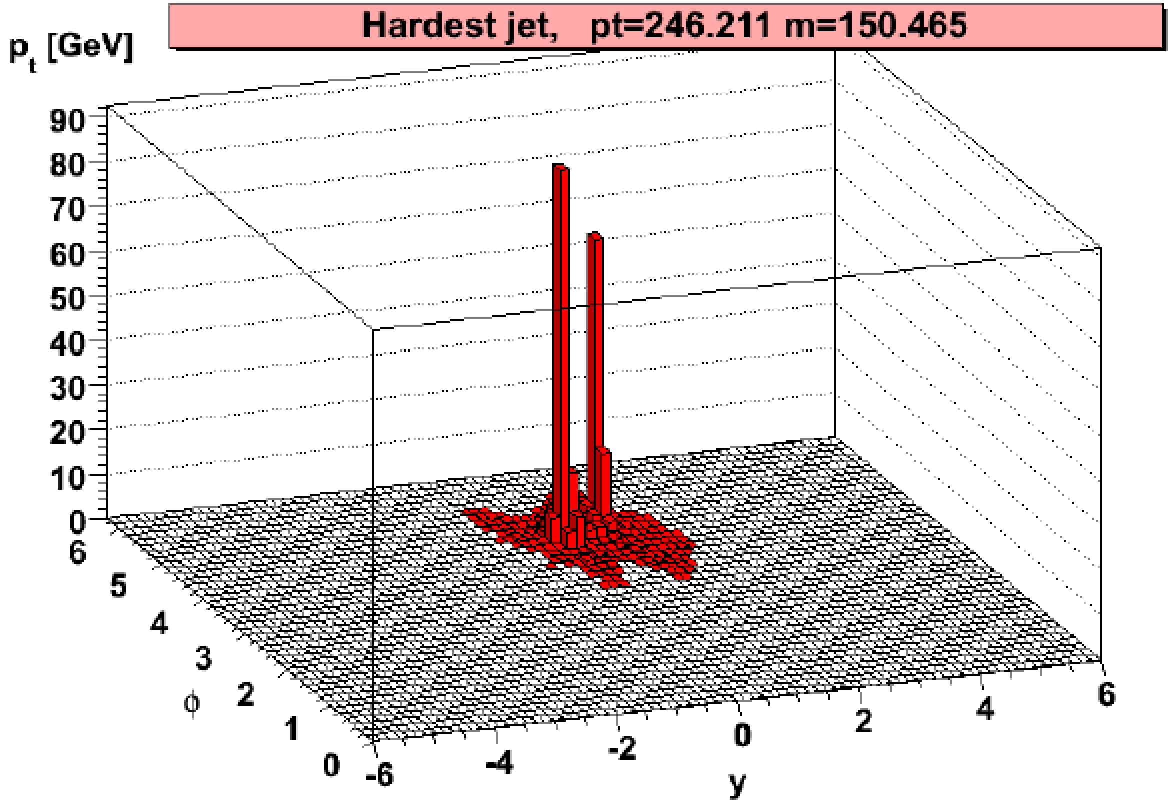
$\delta M \sim R^4 \Lambda_{UE} \frac{p_t}{M}$ [Dasgupta, Magnea & GPS '07]

Filter the jet

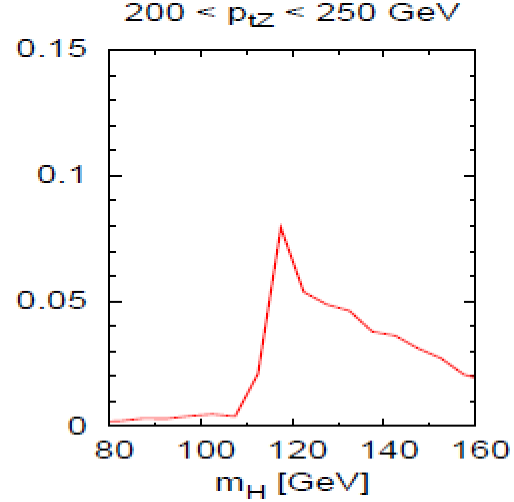
- Reconsider region of interest at smaller $R_{filt} = \min(0.3, R_{b\bar{b}}/2)$
- Take **3** hardest subjets — b, $\bar{b}$ and leading order gluon radiation

$pp \longrightarrow ZH \longrightarrow \nu\bar{\nu}b\bar{b}$, @14 TeV, $m_H = 115$ GeV

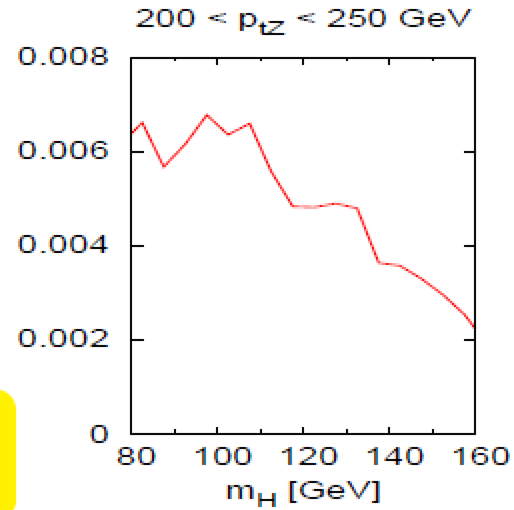
Herwig 6.510 + Jimmy 4.31 + FastJet 2.3



SIGNAL



Zbb BACKGROUND

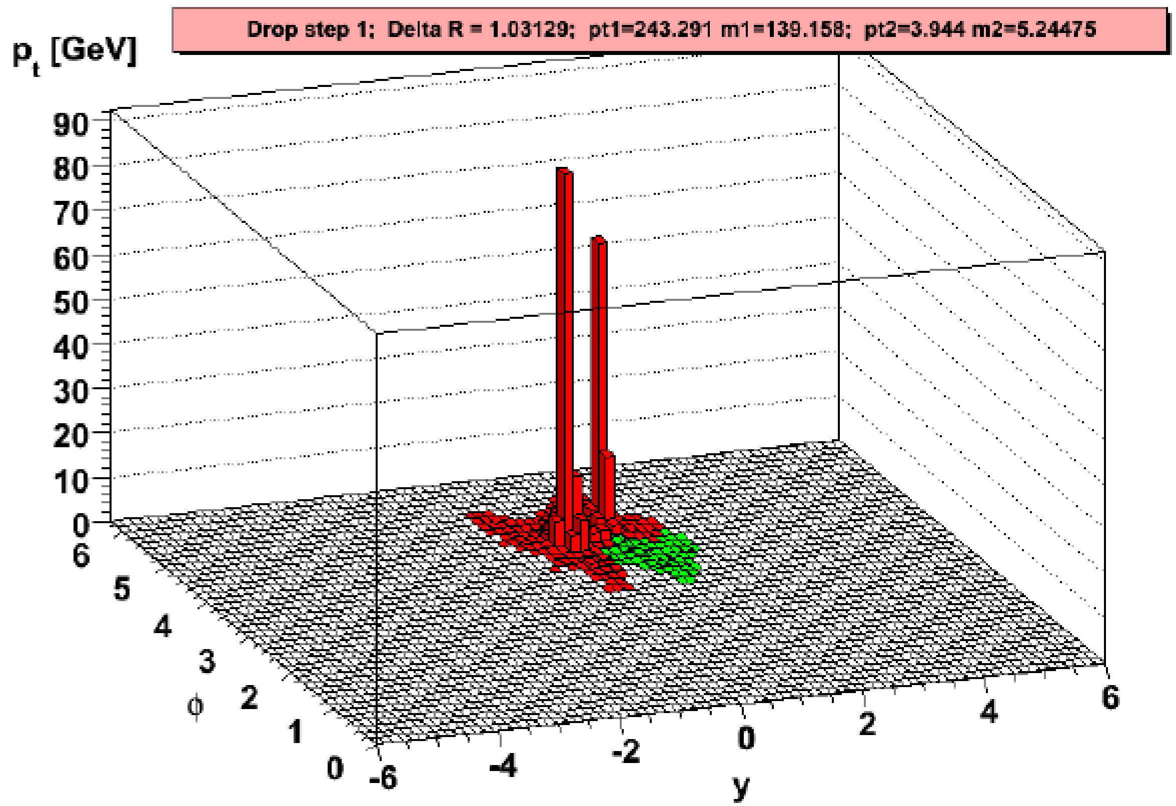


arbitrary norm.

Consider hardest jet, $m = 150$ GeV

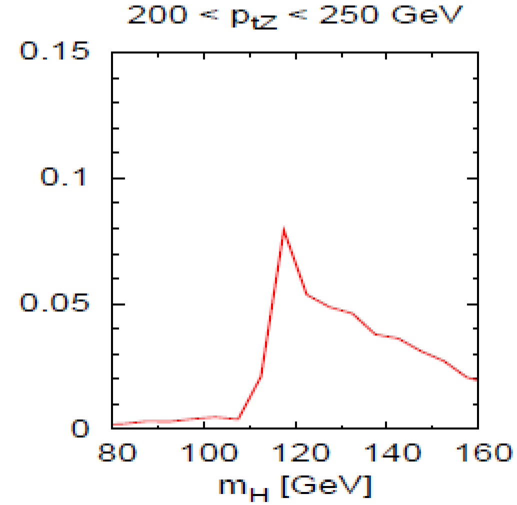
$pp \to ZH \to \nu\bar{\nu}b\bar{b}$, @14 TeV, $m_H = 115$ GeV

Herwig 6.510 + Jimmy 4.31 + FastJet 2.3

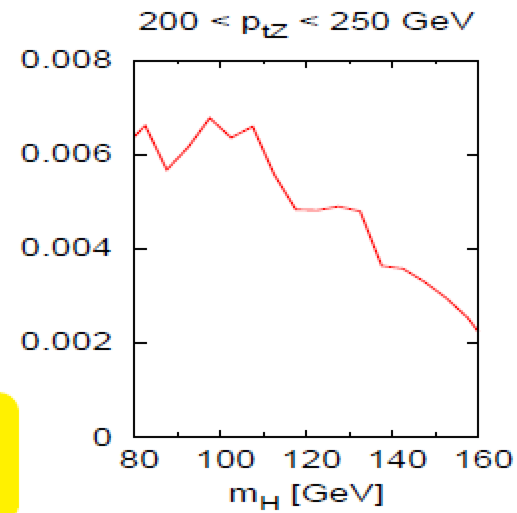


split: $m = 150$ GeV, $\frac{\max(m_1, m2)}{m} = 0.92 \to$ repeat

SIGNAL



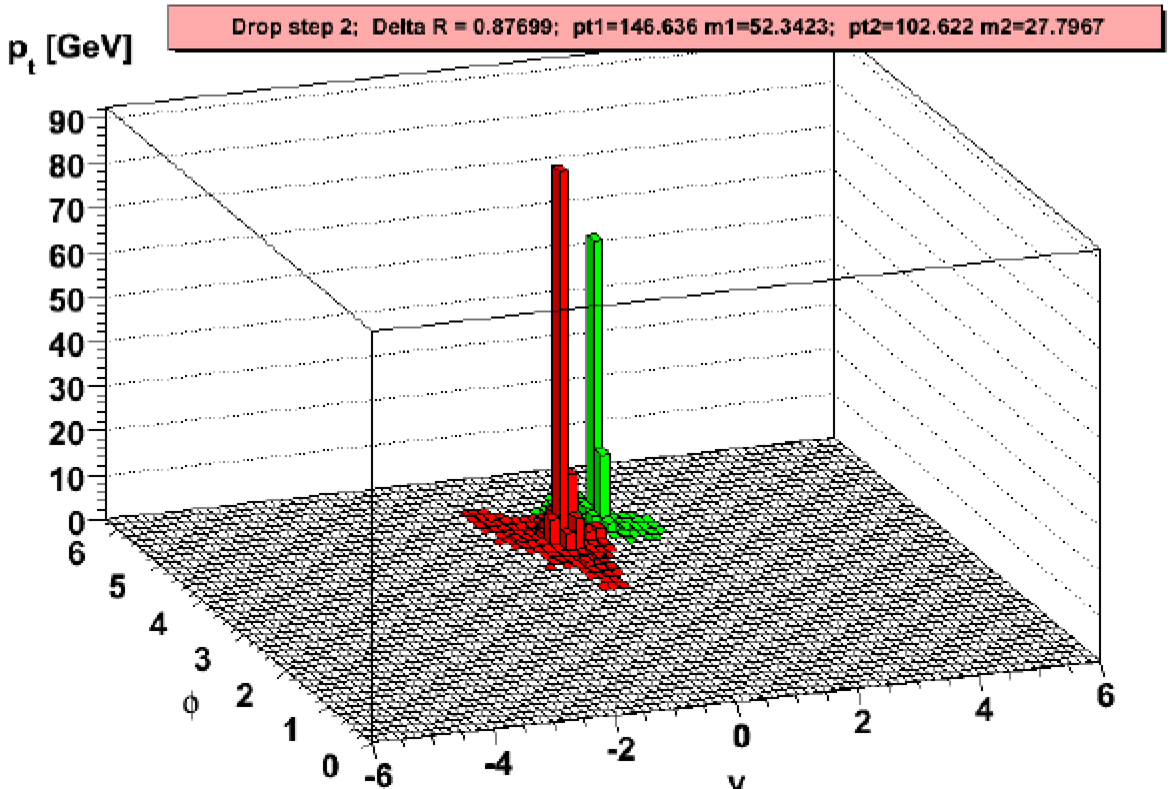
Zbb BACKGROUND



arbitrary norm.

$pp \to ZH \to \nu\bar{\nu}b\bar{b}$, @14 TeV, $m_H = 115$ GeV

Herwig 6.510 + Jimmy 4.31 + FastJet 2.3



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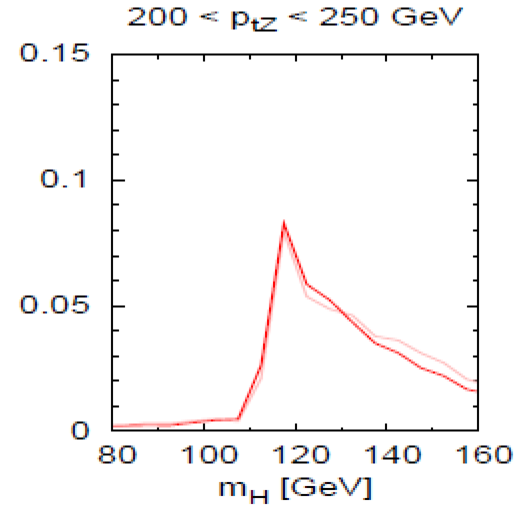
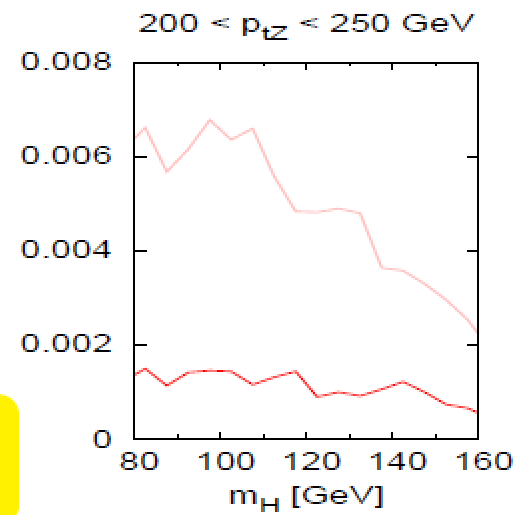


Zbb BACKGROUND

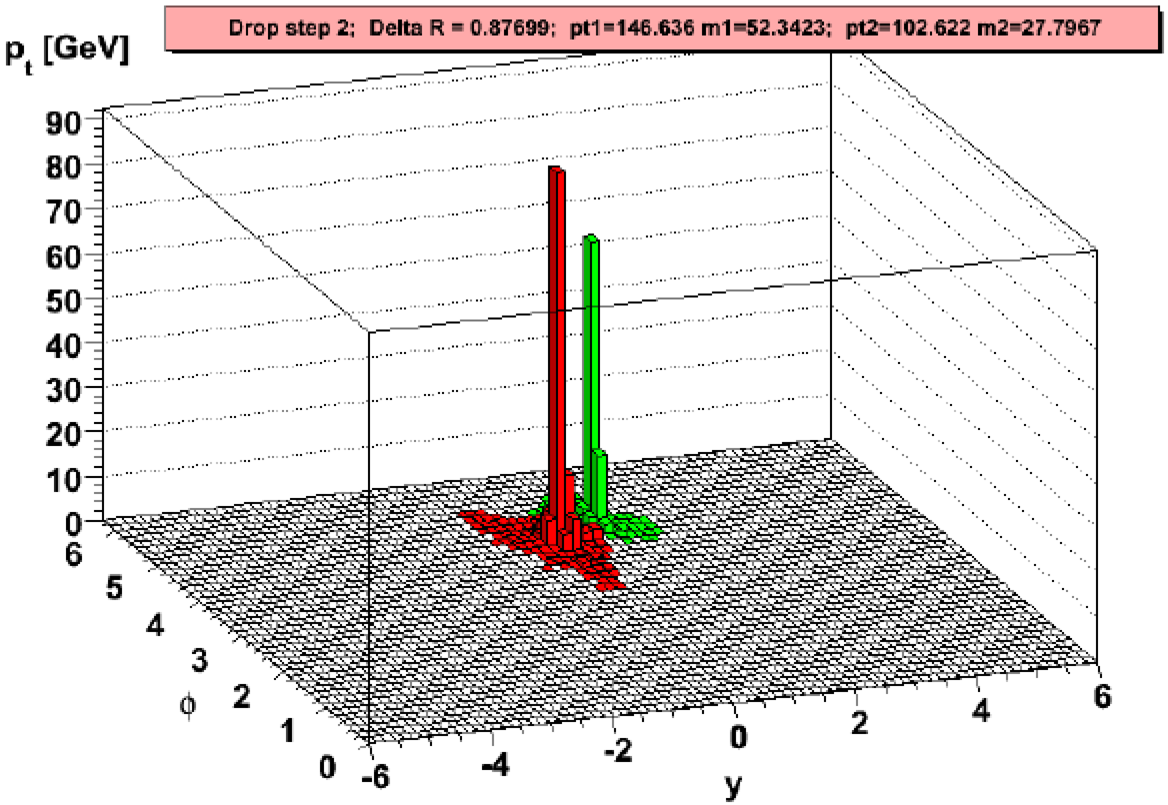


split: $m = 139$ GeV, $\frac{\max(m_1, m2)}{m} = 0.37 \to$ mass drop

arbitrary norm.

$pp \to ZH \to \nu\bar{\nu}b\bar{b}$, @14 TeV, $m_H = 115$ GeV

Herwig 6.510 + Jimmy 4.31 + FastJet 2.3



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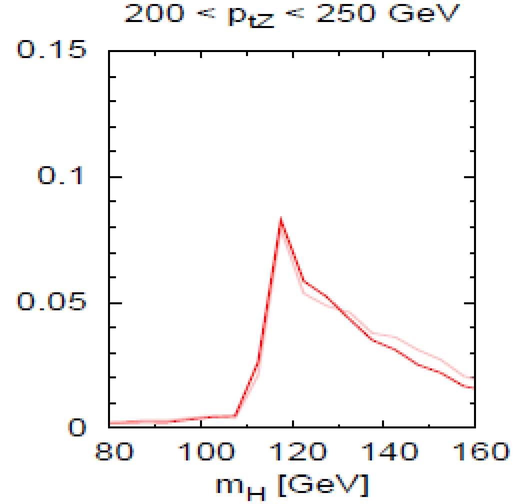
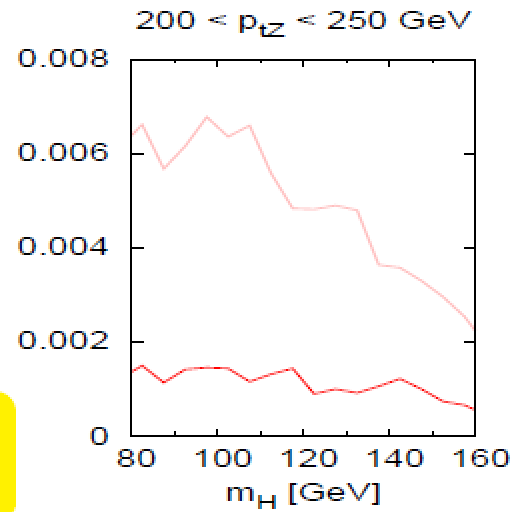


Zbb BACKGROUND

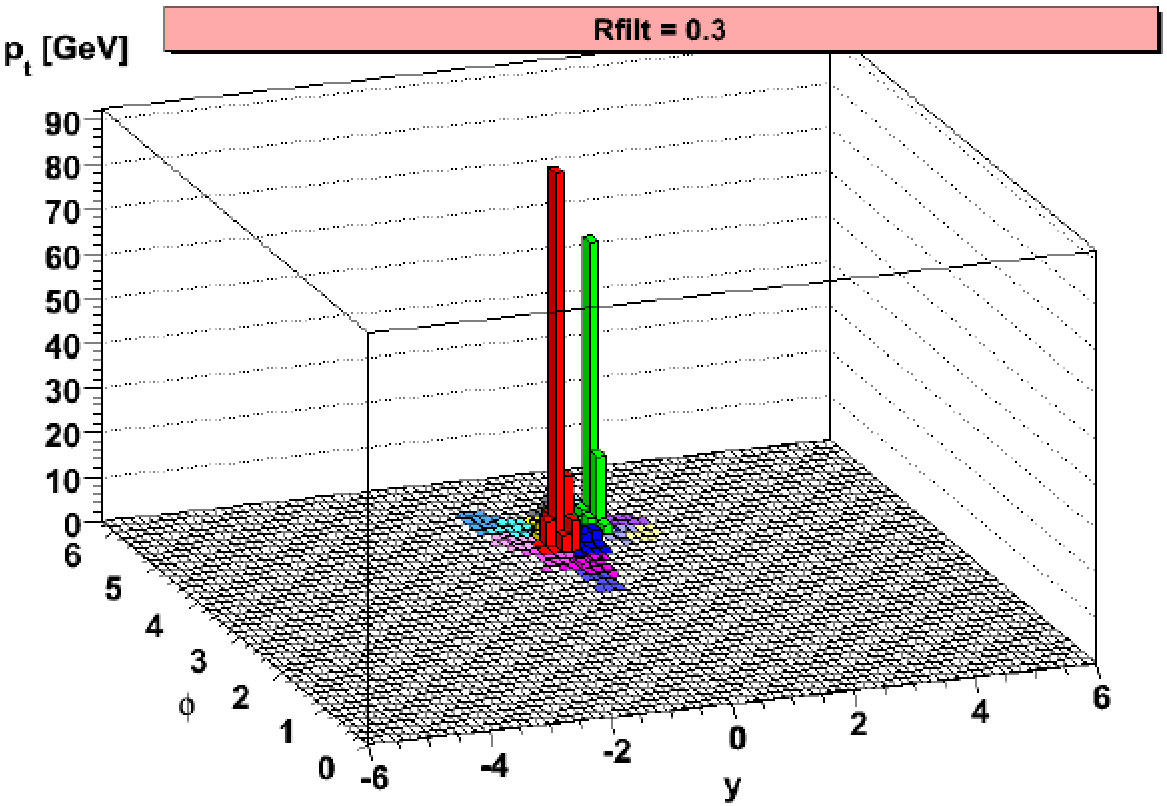


check: $y_{12} \simeq \frac{p_{t2}}{p_{t1}} \simeq 0.7 \to$ OK + 2 b-tags (anti-QCD)

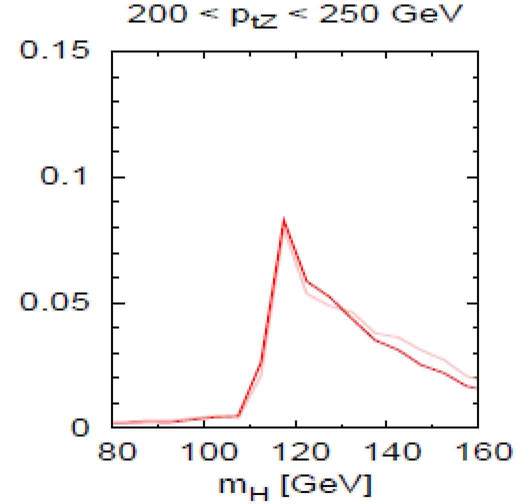
arbitrary norm.

$pp \to ZH \to \nu\bar{\nu}b\bar{b}$, @14 TeV, $m_H = 115$ GeV

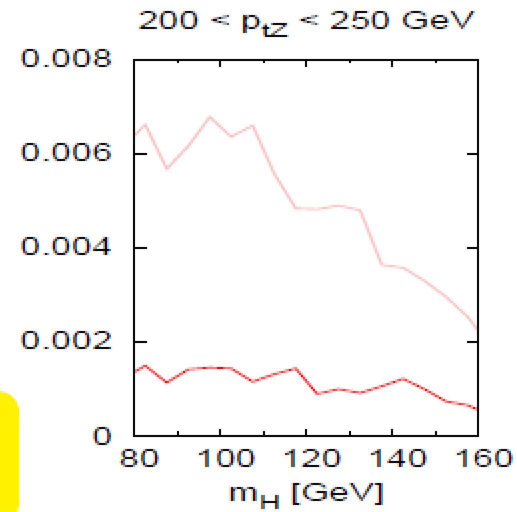
Herwig 6.510 + Jimmy 4.31 + FastJet 2.3



SIGNAL



Zbb BACKGROUND

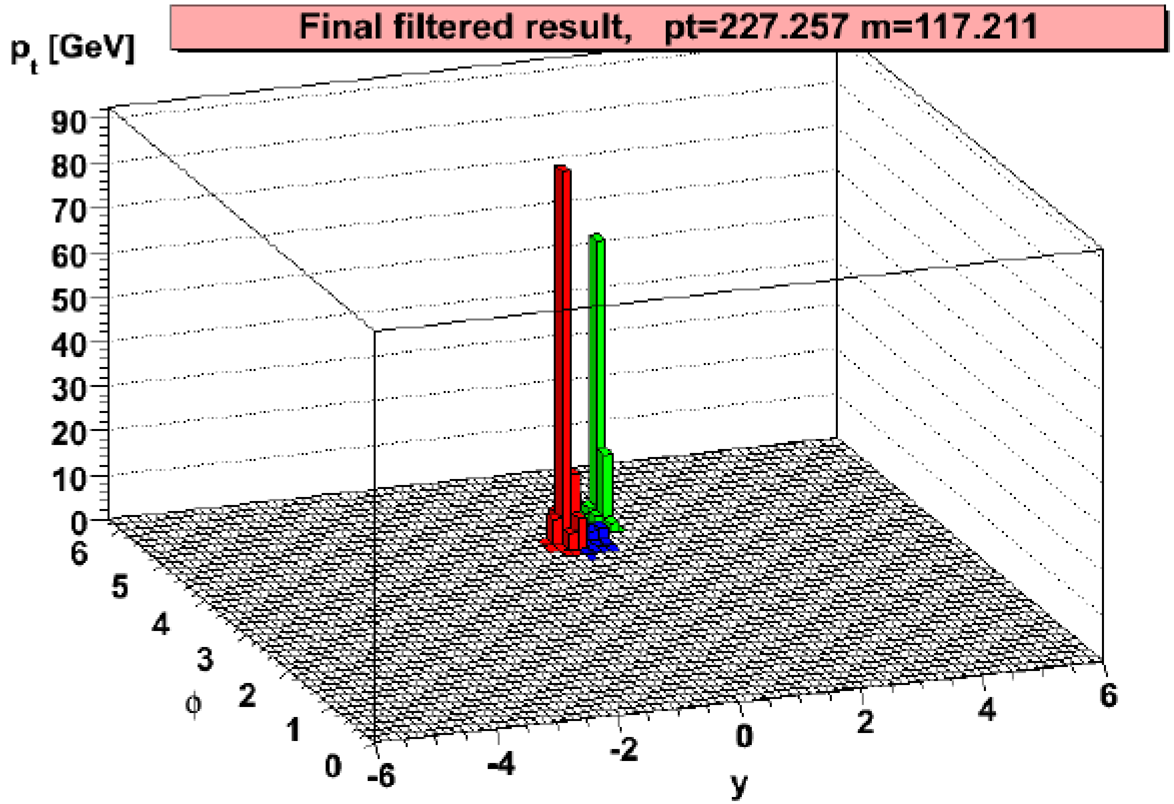


$R_{filt} = 0.3$

arbitrary norm.

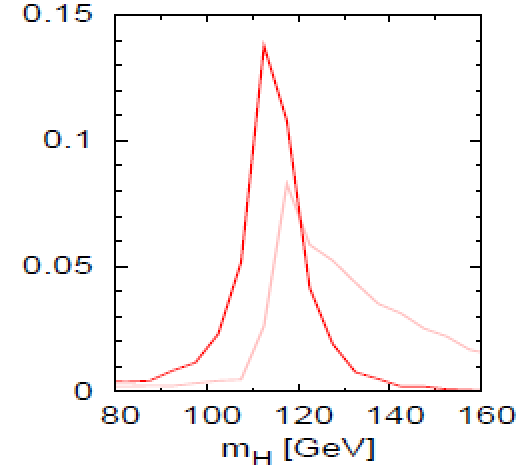
$pp \longrightarrow ZH \longrightarrow \nu\bar{\nu}b\bar{b}$, @14 TeV, $m_H = 115$ GeV

Herwig 6.510 + Jimmy 4.31 + FastJet 2.3



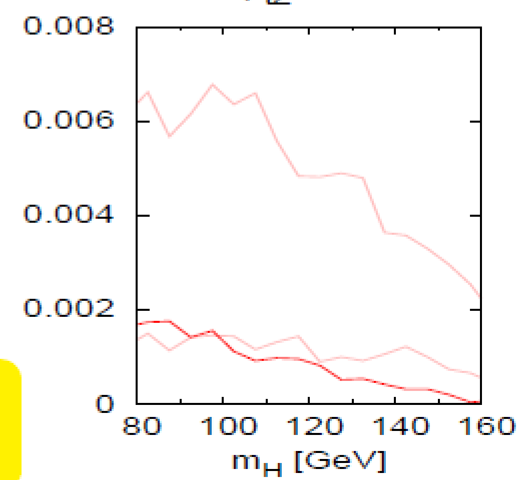
SIGNAL

$200 < p_{tZ} < 250$ GeV



Zbb BACKGROUND

$200 < p_{tZ} < 250$ GeV



$R_{filt} = 0.3$: take 3 hardest, **m = 117 GeV**

arbitrary norm.

End