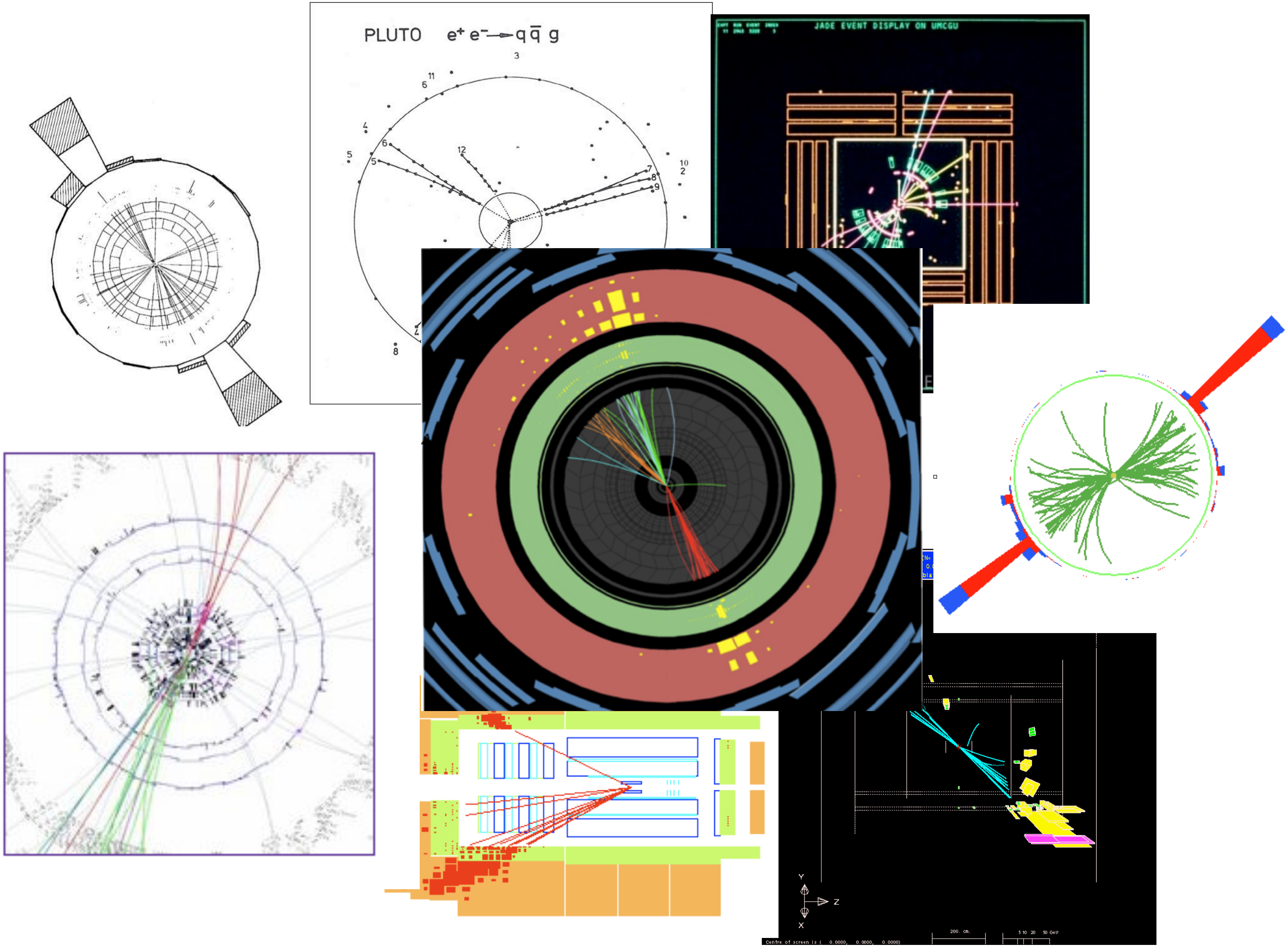
JETS

… a tool for studying "old" and "new" physics …

Thomas Schörner-Sadenius

DESY "Tuesday" Seminar, 24 March 2011


JET
AIR FRANCE
JET
FunnyAnimalSite.com


PLUTO $e^+ e^- \to q \bar{q} g$
JADE EVENT DISPLAY ON UMCGU
Y
Z
X
200. cm.
Centre of screen is (0.0000, 0.0000, 0.0000)

OVERVIEW

¶ HISTORY OF JETS, AND BASIC CONCEPTS
- History: jets in hadron collisions and e^+e^-
- Jet algorithms
- Theoretical predictions

¶ JETS AT HERA, TEVATRON etc. – AND WHAT DID WE LEARN?

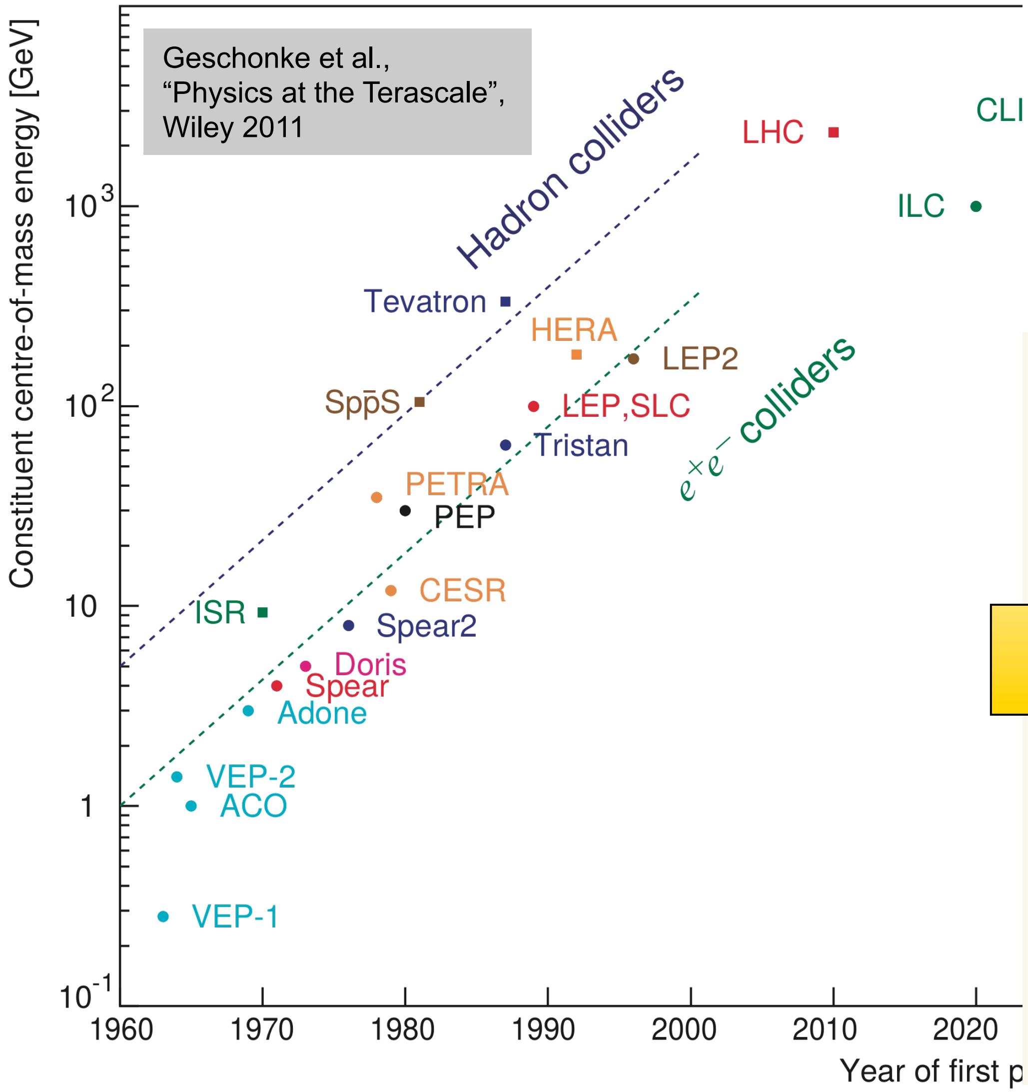
¶ JETS AND QCD AT THE LHC

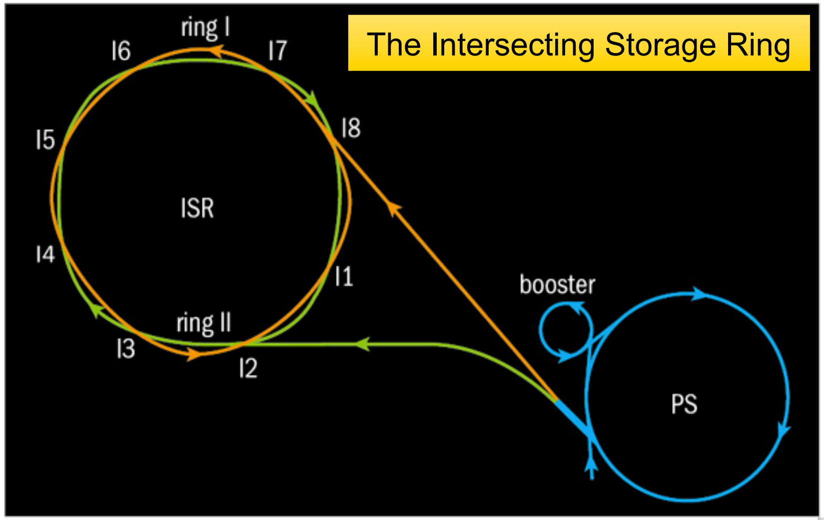
¶ JETS, NEW CONCEPTS AND NEW PHYSICS

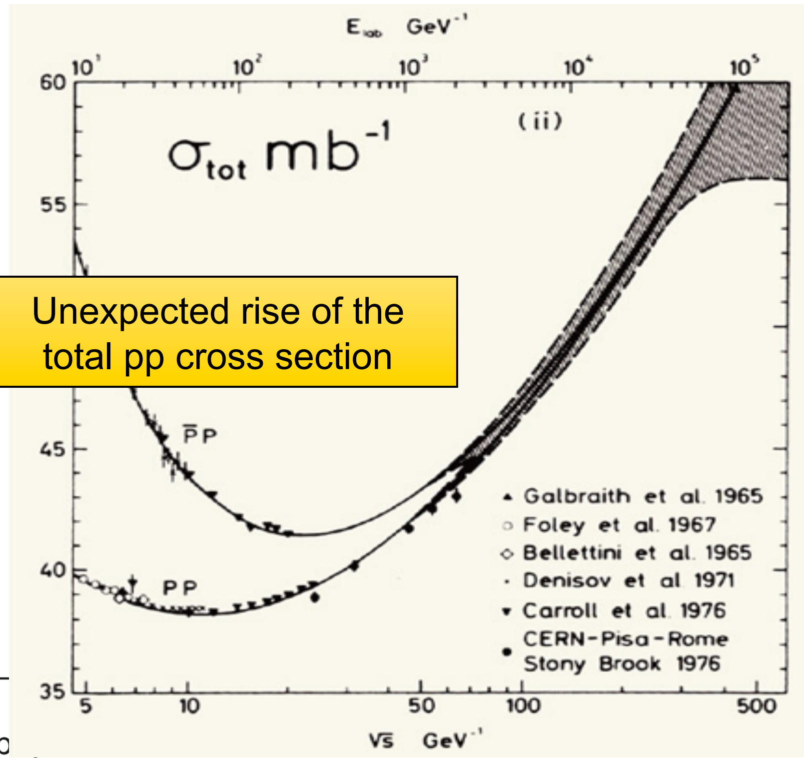
¶ Not covered: jets and flavour, gluon versus quark jets, jets and top physics, jets and SUSY, most of jets in e^+e^- and 2γ, …

HISTORY OF JETS

Intersecting Storage Ring



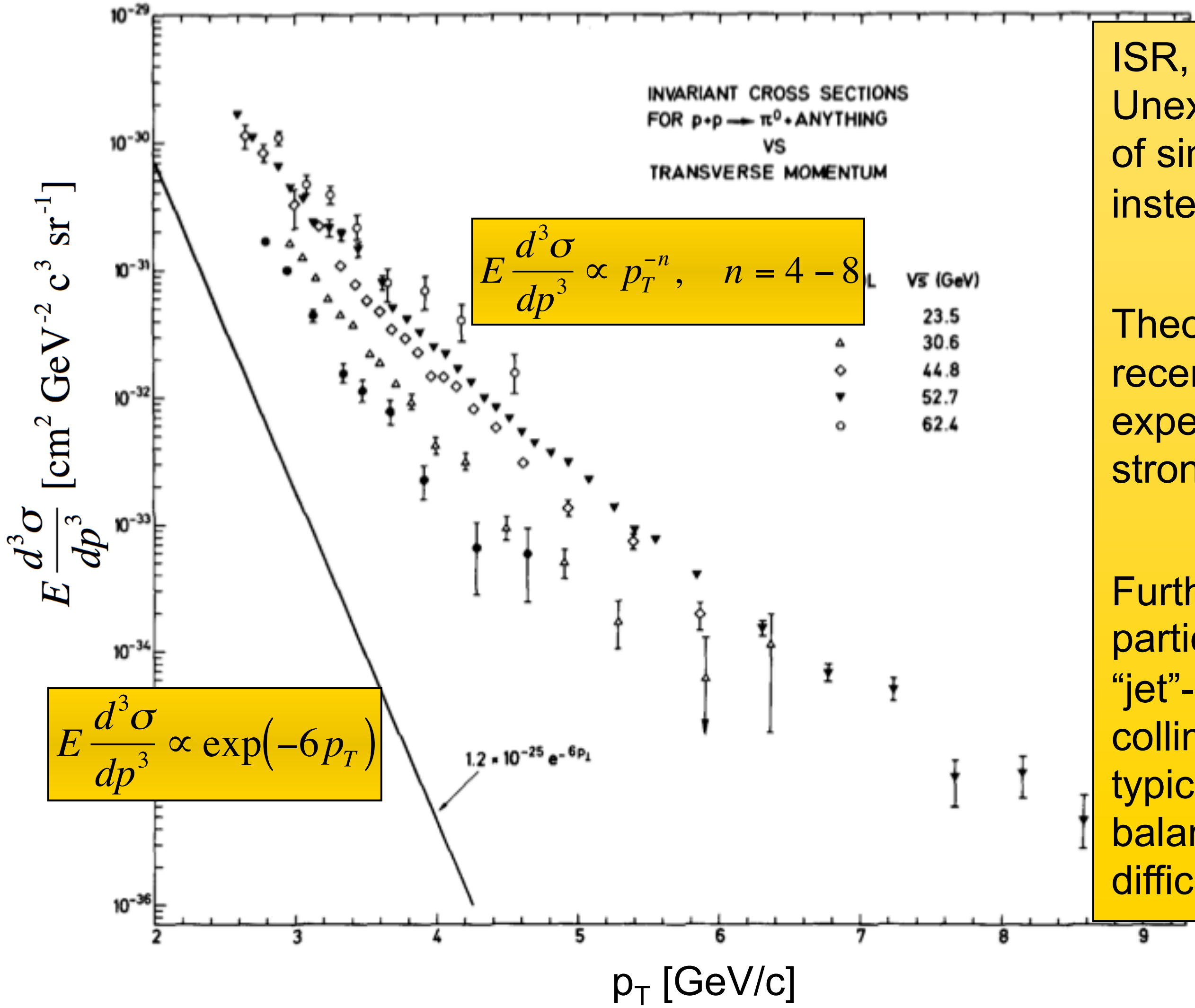




Unexpected rise of the total pp cross section

HISTORY OF JETS

The ISR – the "high-p_T" phenomenon



ISR, 1973 (Büsser et al.): Unexpected high-p_T behaviour of single particles: Power law instead of exponential!

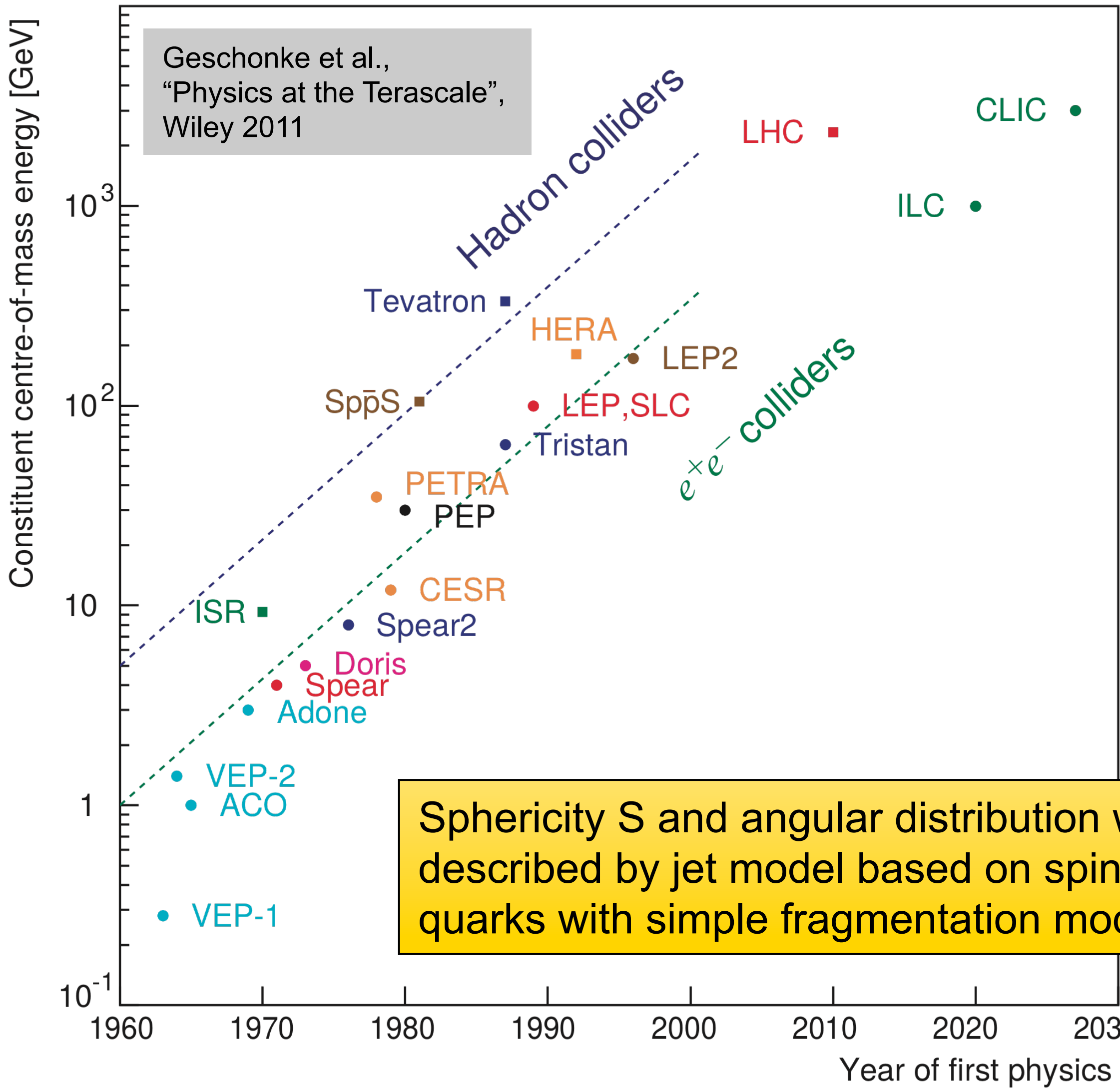
Theoretically expected because of recent deep-inelastic scattering experiments and parton picture of strong interactions (Bjorken et al.).

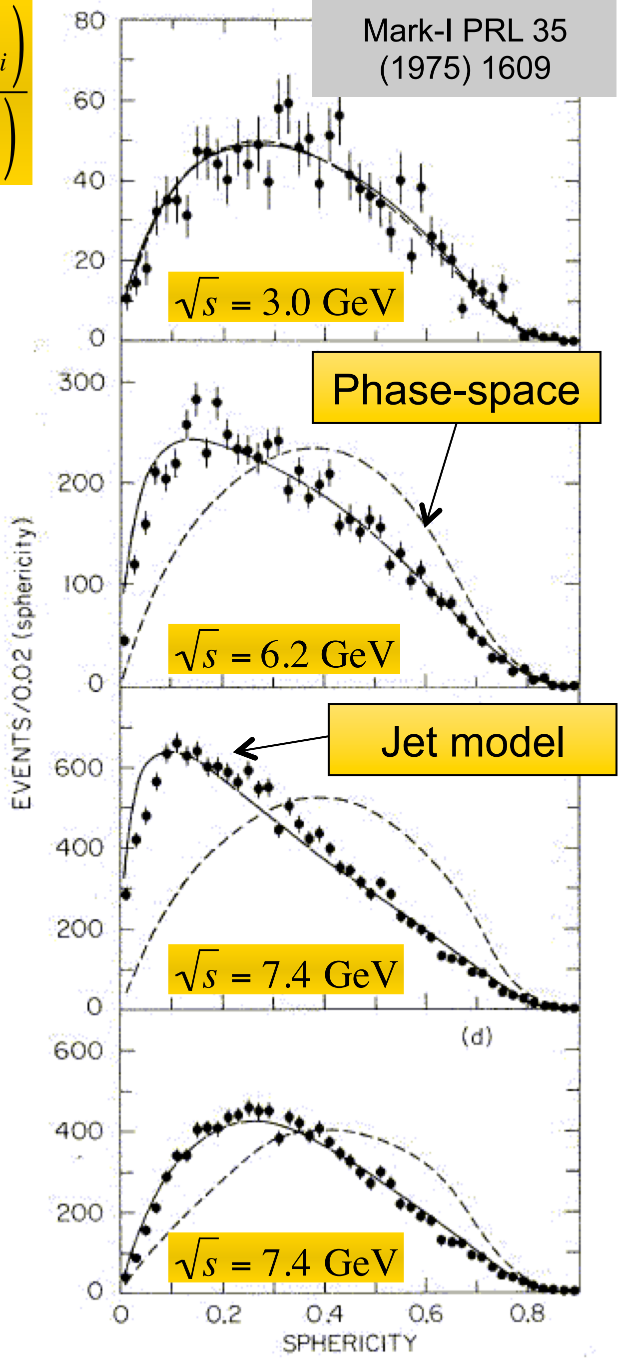
Further hypothesis: high-p_T particles often accompanied by "jet"-like structures ("cores") – collimated bundles of hadrons; typical event consists of pair of jets balanced in p_T. Experimentally difficult to confirm.

HISTORY OF JETS

e⁺e⁻ collisions at SPEAR

$$S = \frac{3\left(\sum_i p_{T,i}^2\right)}{2\left(\sum_i p_i^2\right)}$$





Sphericity S and angular distribution well described by jet model based on spin-1/2 quarks with simple fragmentation model .

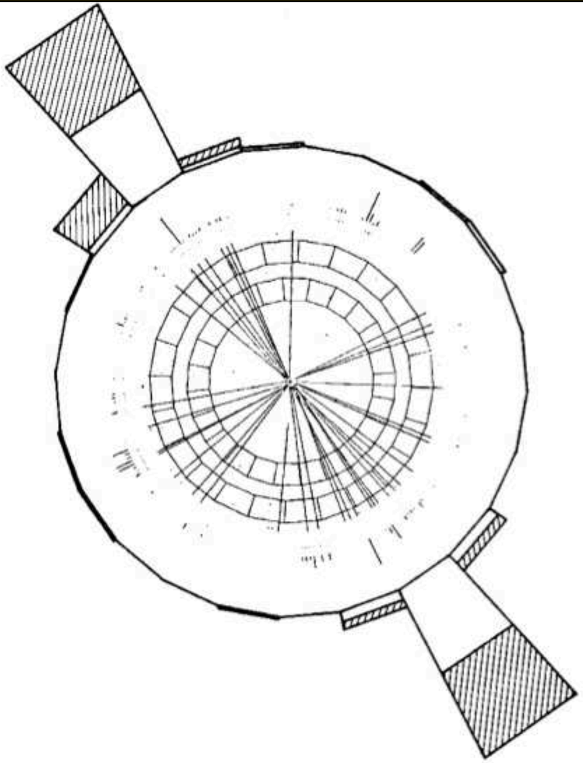
HISTORY OF JETS

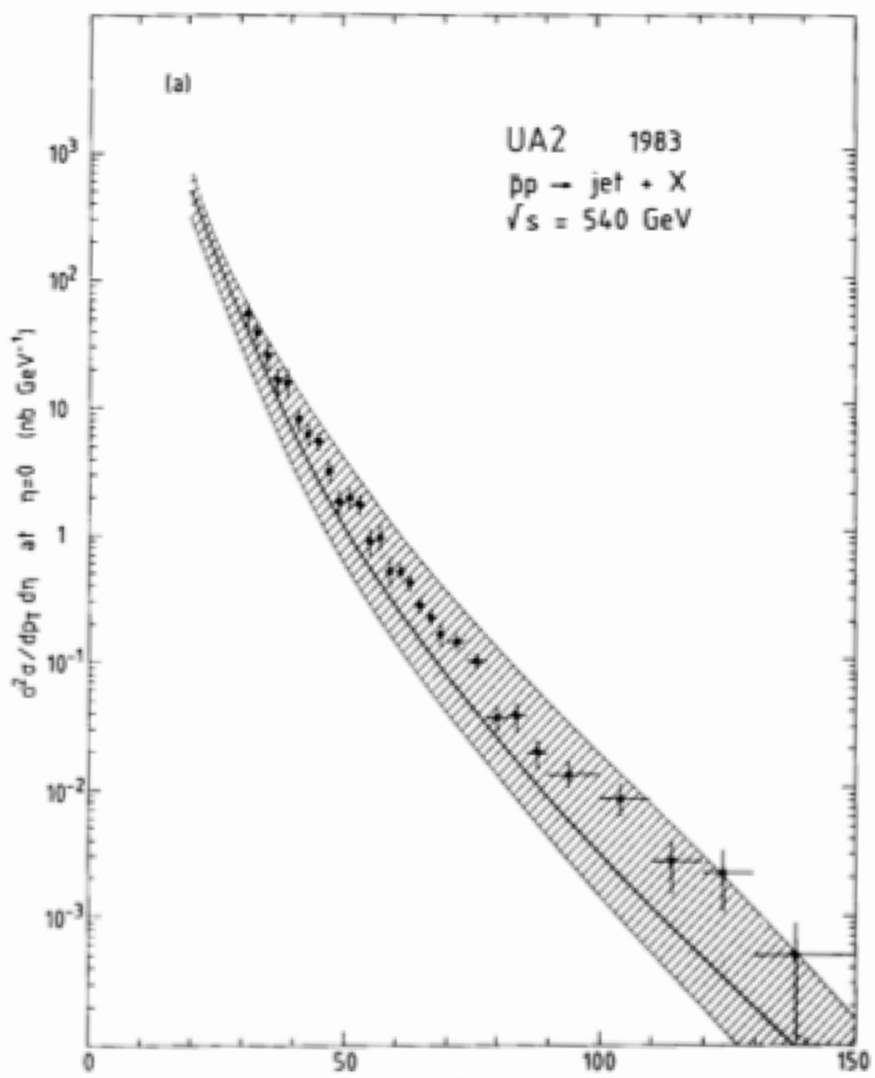
Confirmation in hadron collisions: the ISR and the SppS

UA2 (SppS) and AFS (ISR) 1984:

Clear evidence for hard parton-parton interactions and jets, described in pQCD!

Since these times jets considered as final-state objects like electrons etc.





Jet p_T [GeV/c]

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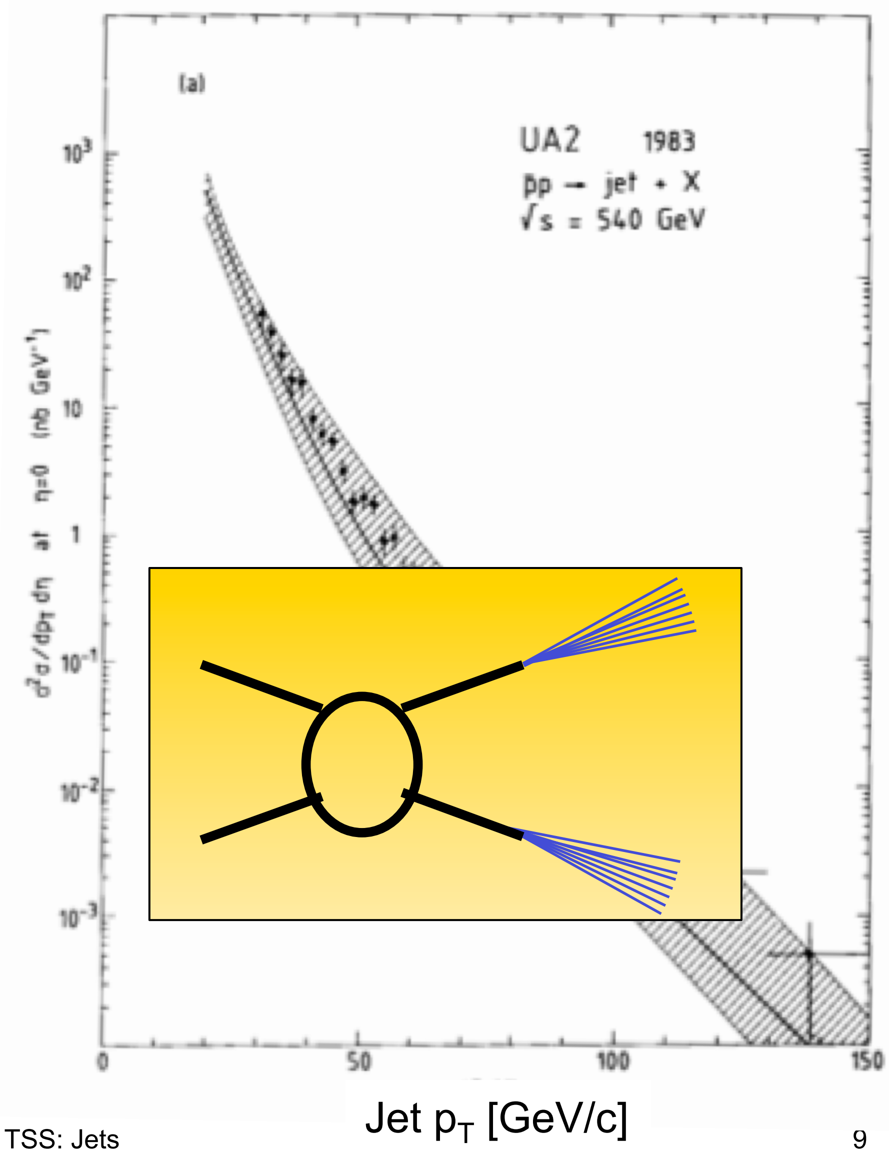


Lessons learned:
Spin-1/2 partons (quarks) as outcome of hard scattering. Partons then shower / hadronise.

No large p_T created during showering / hadronisation → collimated bundles: jets

Jet algorithm: Calculating back from the final-state activity to the partonic event.

INFRARED AND COLLINEAR SAFETY

… and other requirements on jets …

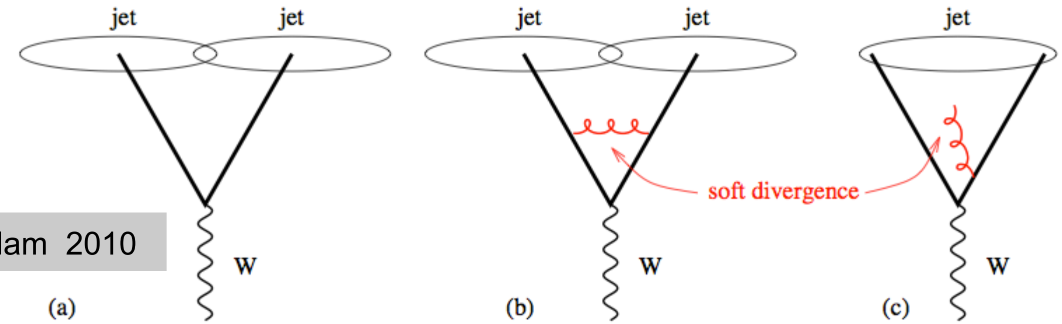
Several requirements on jet algorithms …

… like efficiency, small experimental corrections, applicability to detector objects like CAL energies, tracks, to MC hadrons and to partons from fixed-order calculations etc.

Infrared and collinear safety:

Jet final state unaffected by soft / collinear radiation!

Salam 2010



First jet algorithm:
Sterman-Weinberg summing convention for e^+e^- events

Allowed to have perturbative QCD calculation for probability of two-jet events.

Sterman and Weinberg 1977

Then soon different directions developed:

“Sequential recombination” algorithms (e^+e^-); merge particles according to “distance”

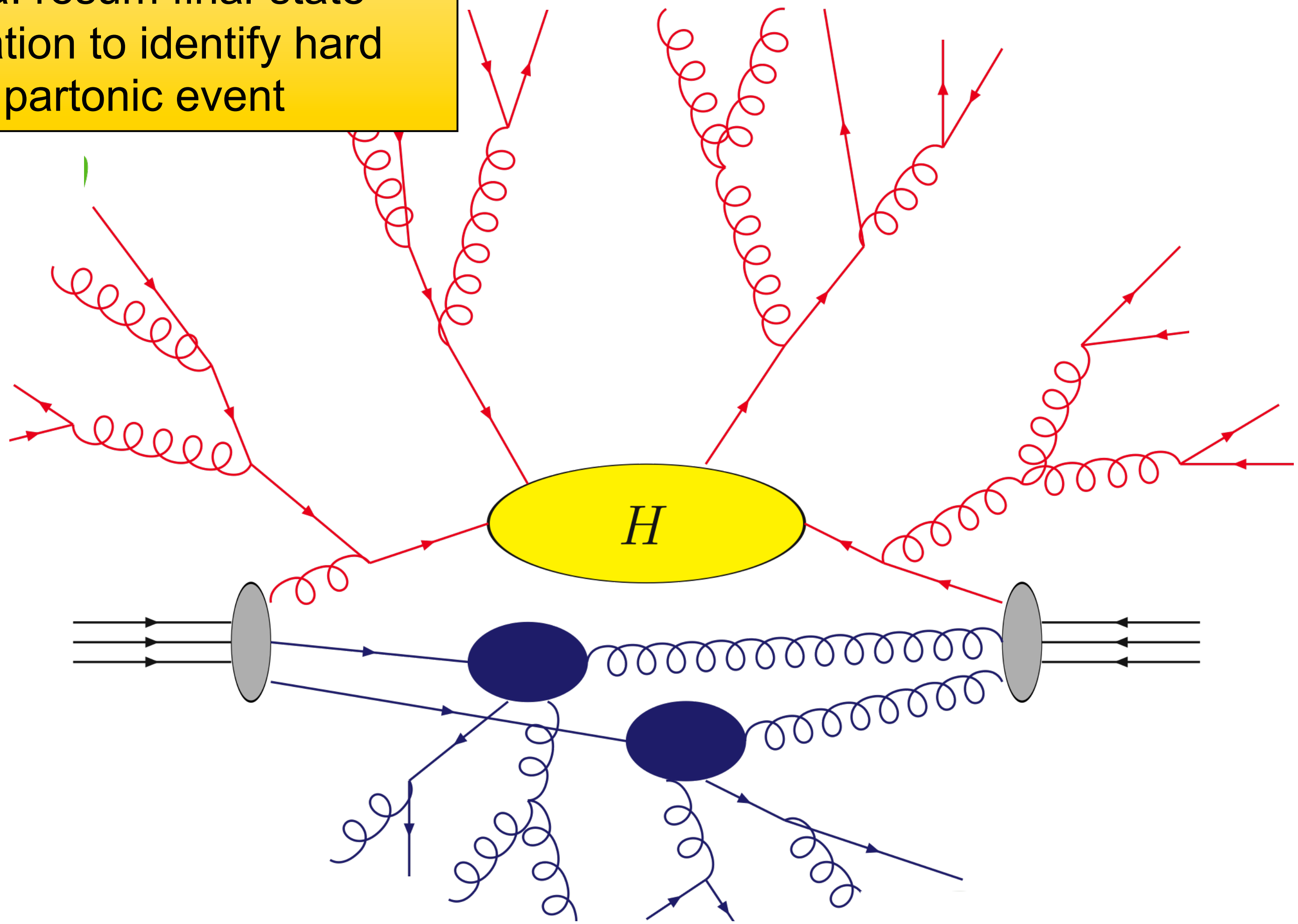
“Cone-type” algorithms; jet = dominant direction of energy flow.

“Event decomposition algos” (DECO), ARCLUS… (only of historical interest)

CLUSTERING ALGORITHMS

"Sequential recombination algorithms"

Idea: resum final-state radiation to identify hard partonic event



Picture Z. Nagy

CLUSTERING ALGORITHMS

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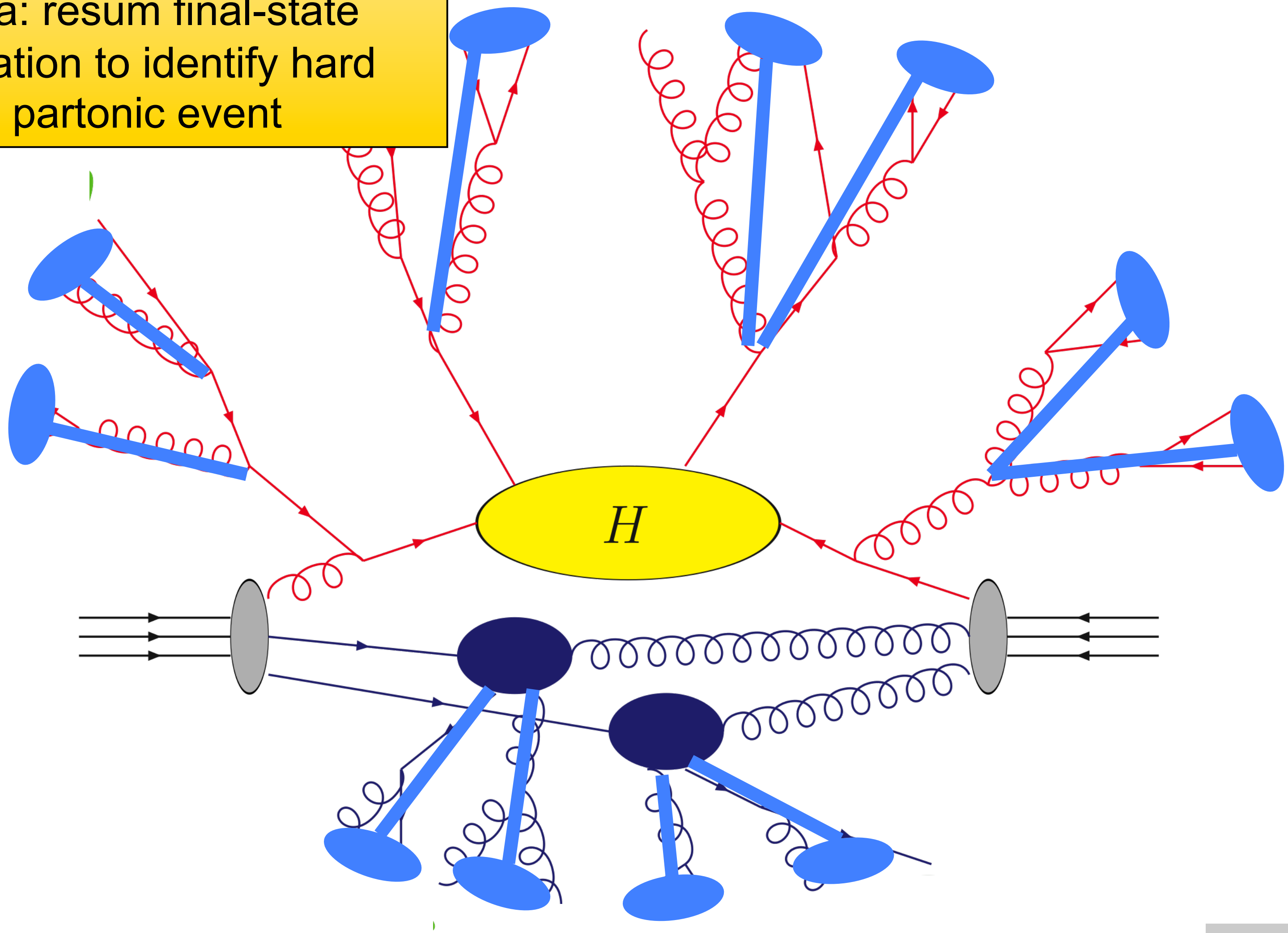

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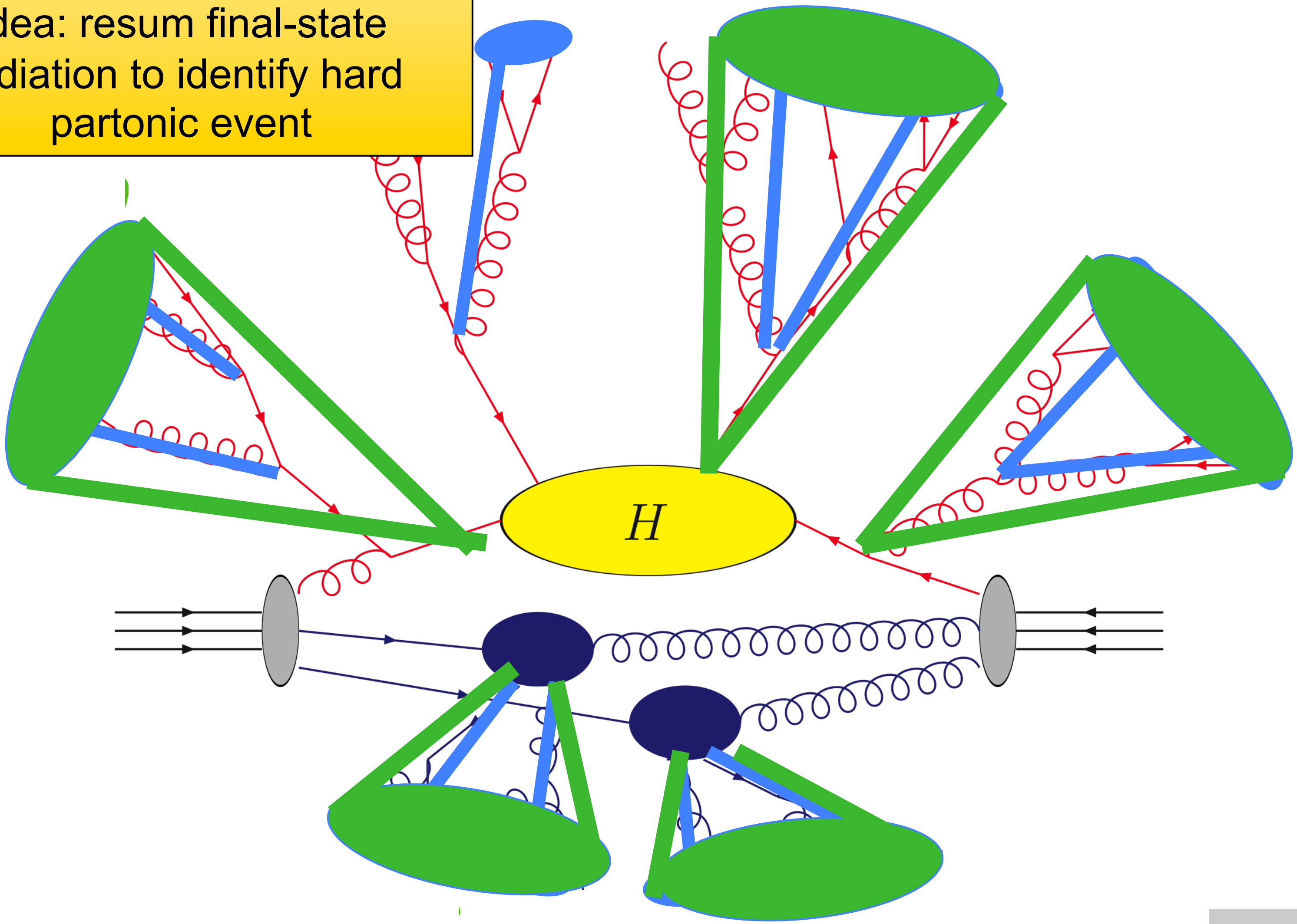

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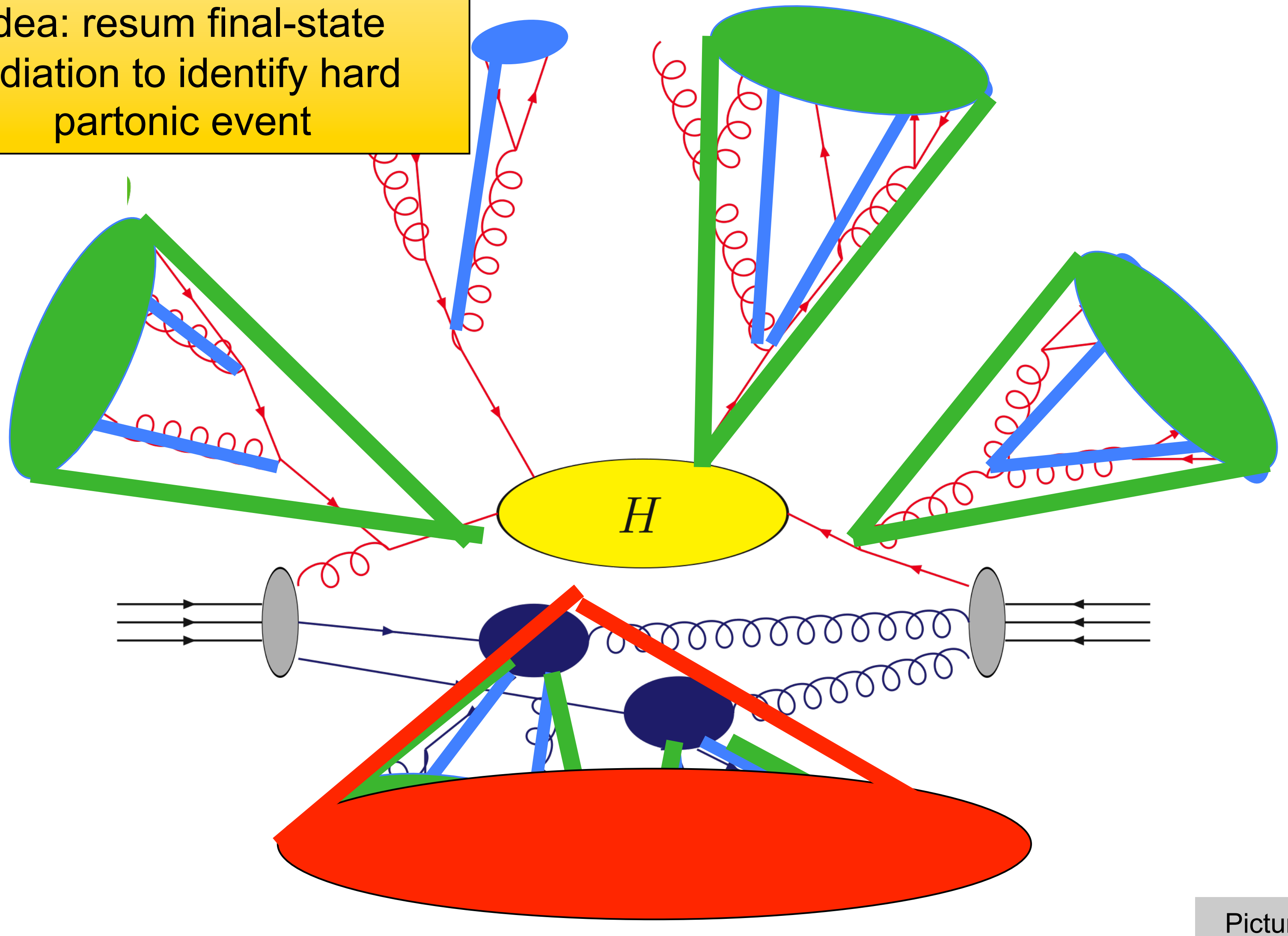


Picture Z. Nagy

CLUSTERING ALGORITHMS

“Sequential recombination algorithms”

Many implementations – differing in distance criterion

– early example: JADE algorithm; also Cambridge-Aachen, deterministic annealing, “optimal jet finder”, ARCLUS, …)

k_T algorithm in e^+e^- physics:

Catani et al. 1991

–in collinear limit, numerator → $k^2_{T,ij}$ → name!

– distance measure ~ inverse of splitting probability for soft collinear splitting

$$y_{ij} = \frac{2\min\left(E_i^2, E_j^2\right)\left(1-\cos\theta_{ij}\right)}{Q^2}$$

k_T algorithm with incoming hadrons:

Ellis et al. 1993

– total event energy Q not known → dimensionful distance

– distance to beam d_{iB}: isolation of beam jet(s).

$$d_{ij} = \min\left(p_{Ti}^2, p_{Tj}^2\right)\frac{\Delta R_{ij}^2}{R^2}$$

$$d_{iB} = p_{Ti}^2$$

Rather recently: anti-k_T algorithm:

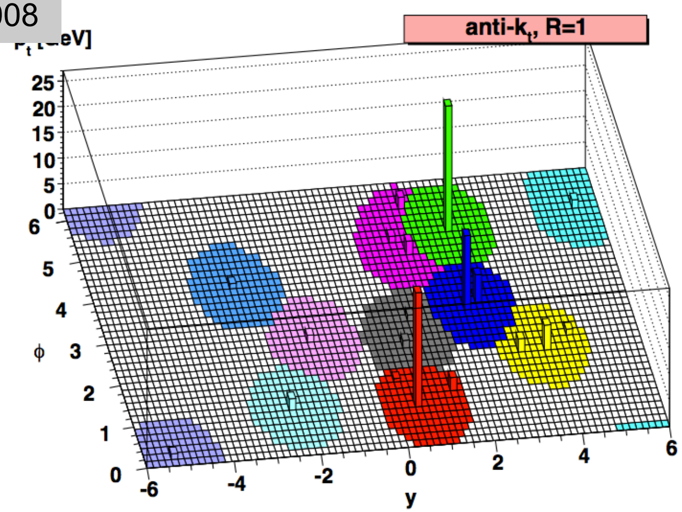
Cacciari et al. 2008

– Clustering focuses on hard splittings, combines particles starting from hard “seed”.

$$d_{ij} = \min\left(p_{Ti}^{-2}, p_{Tj}^{-2}\right)\frac{\Delta R_{ij}^2}{R^2} \quad d_{iB} = p_{Ti}^{-2}$$

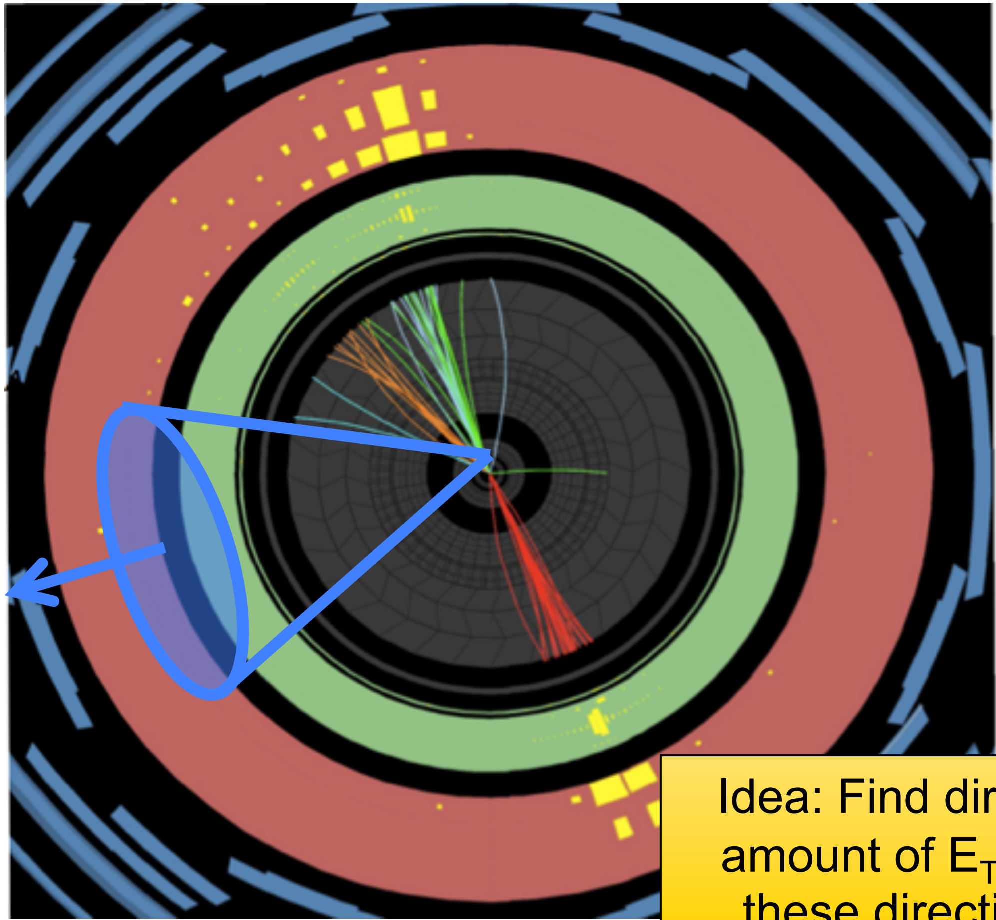
– Infrared and collinear safe, round jets.

– Default at the LHC



CONE-TYPE ALGORITHMS

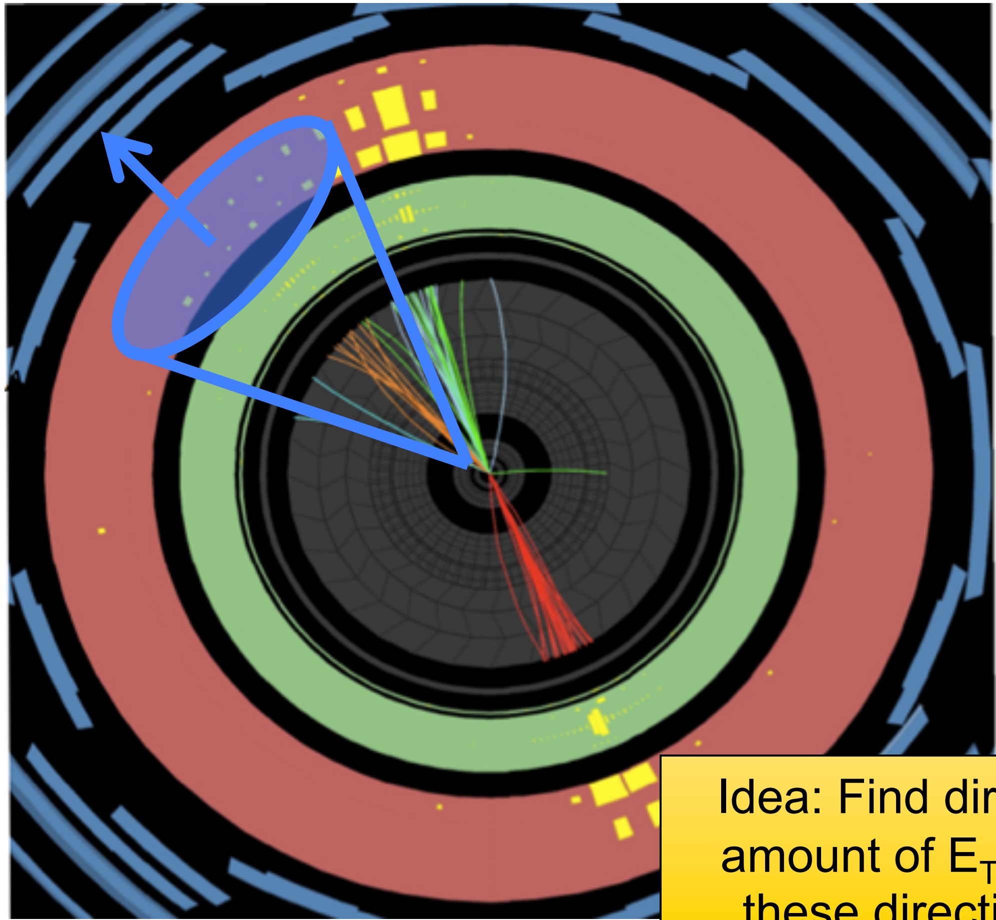
Maximising the energy in geometric cones



Idea: Find directions such that amount of E_T in cones around these directions is maximal.

CONE-TYPE ALGORITHMS

Maximising the energy in geometric cones



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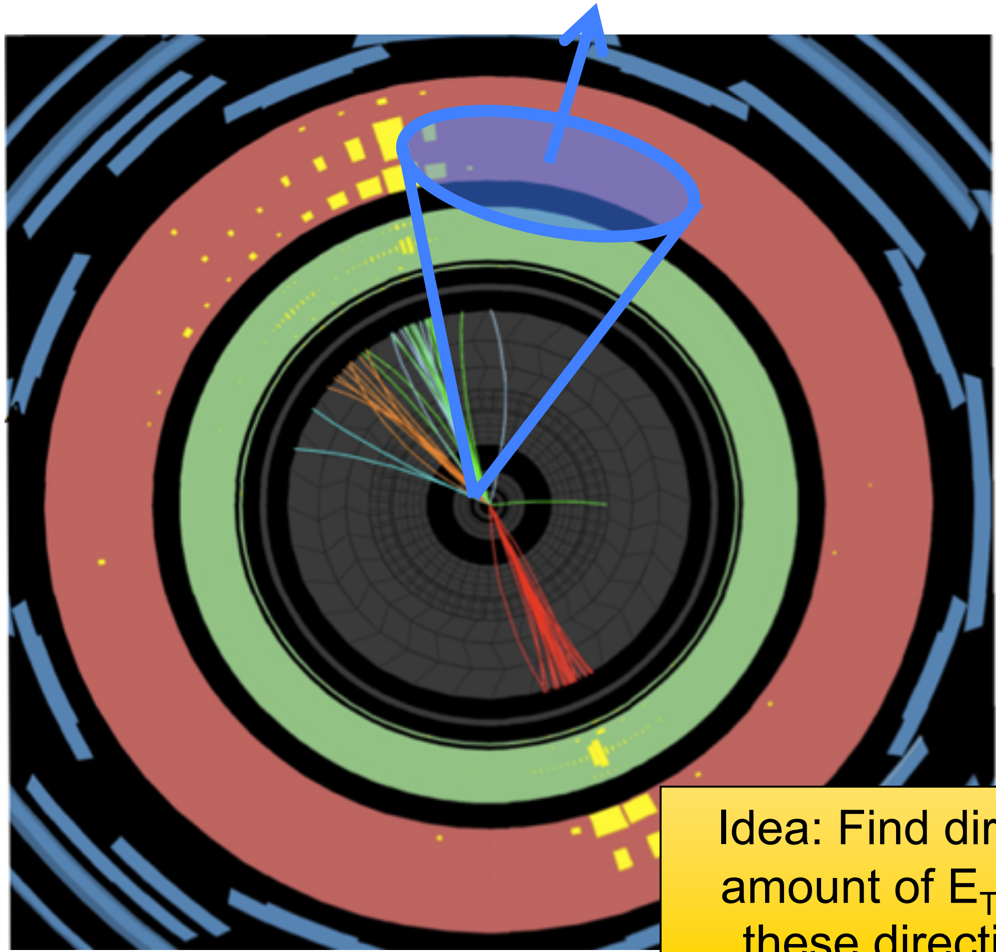

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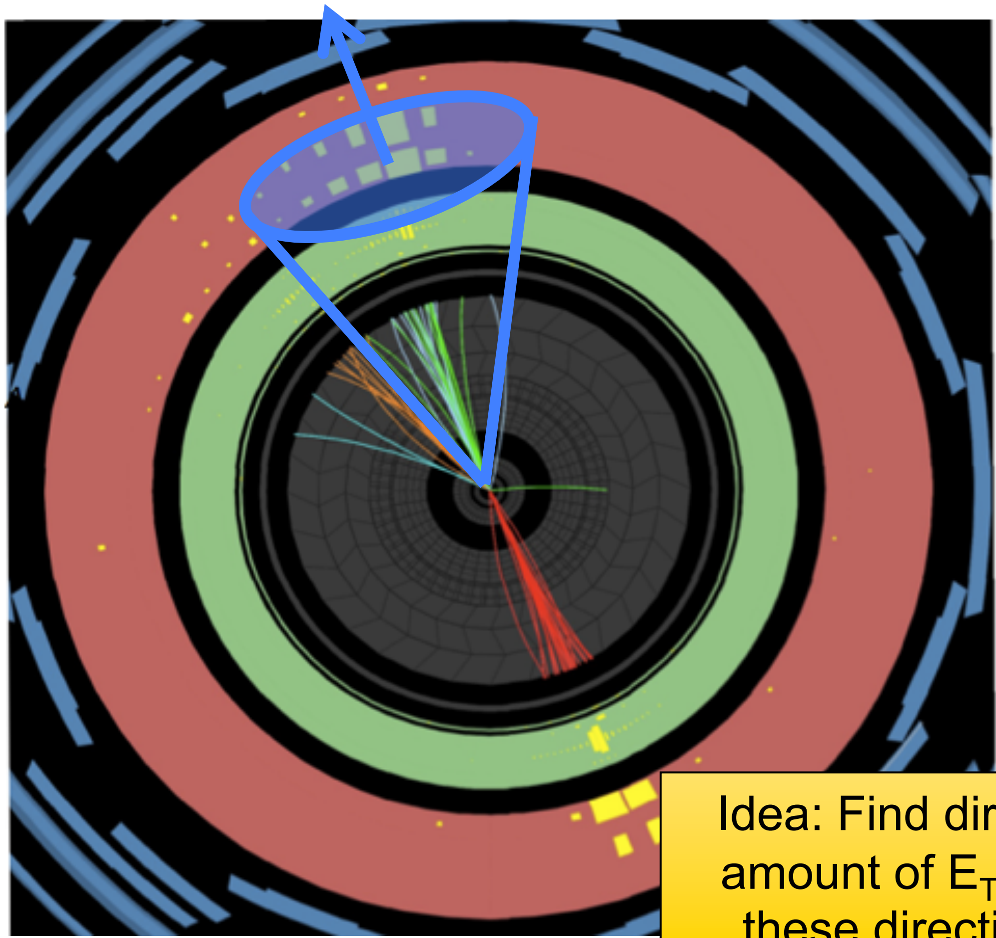


Idea: Find directions such that amount of E_T in cones around these directions is maximal.

CONE-TYPE ALGORITHMS

Maximising the energy in geometric cones

Long history of different implementations, especially at the Tevatron:

- Idea: looking for "stable cones" in which sum of momenta of all particles points in the same direction as the axis of the cone.
- often starting from seed directions and then iterating.

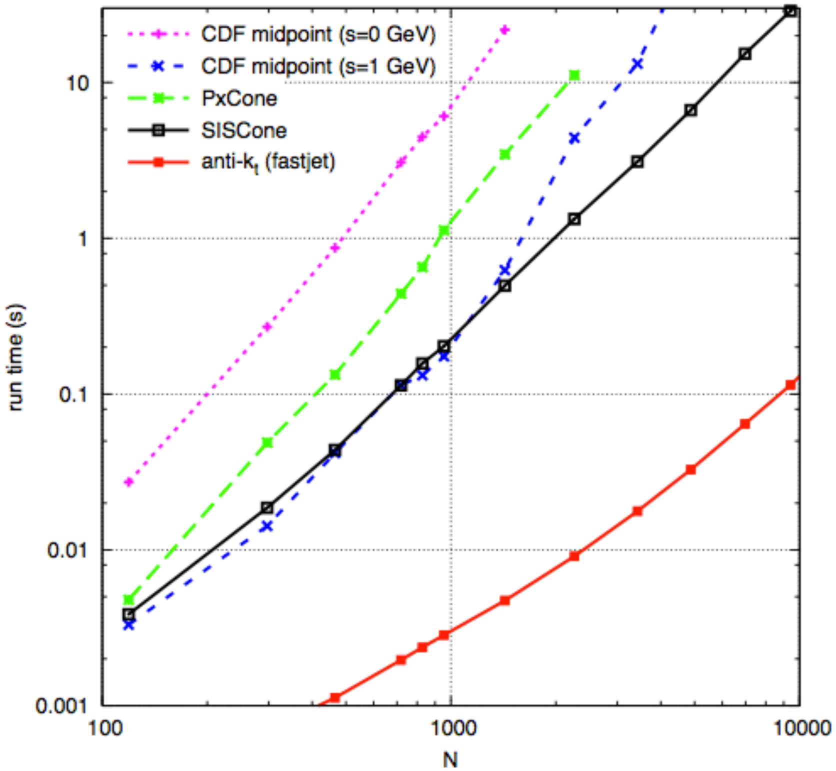
Often issues with

- infrared and collinear safety (especially in theory predictions at higher orders).
- treatment of overlapping cones
- Choice of seeds for initial cones.
- computational speed, etc.

➔ exact seedless and infrared cone algorithm: SISCone

Salam et al. 2007

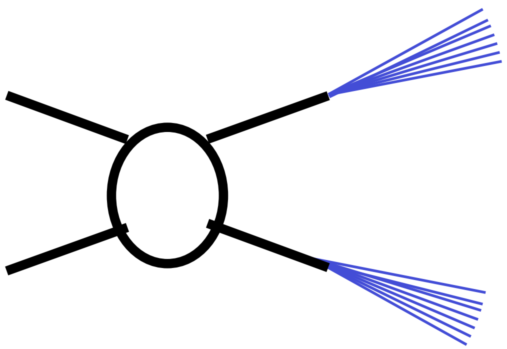
- seedless in order to not miss stable cones
- Reducing problem of jet finding to one of computational geometry.
- Excellent performance in terms of time and IR / coll. safety.



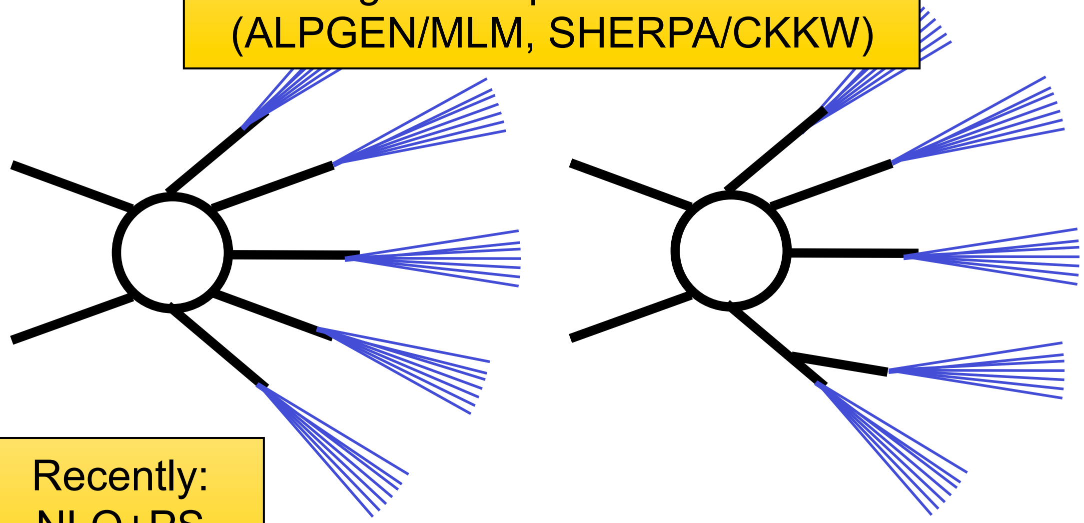
JETS IN THEORY

Monte Carlo, fixed-order, and the best of both worlds …

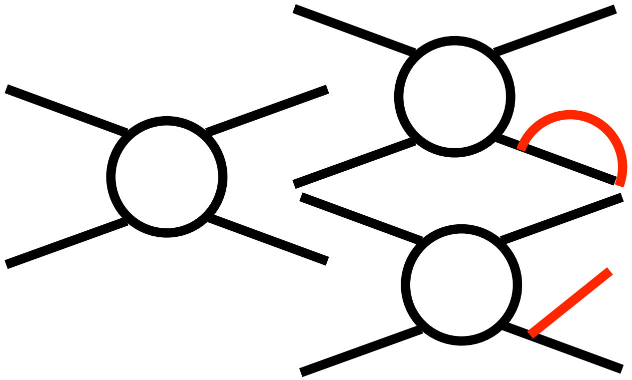
2→2 matrix elements with parton shower (PYTHIA, HERWIG)



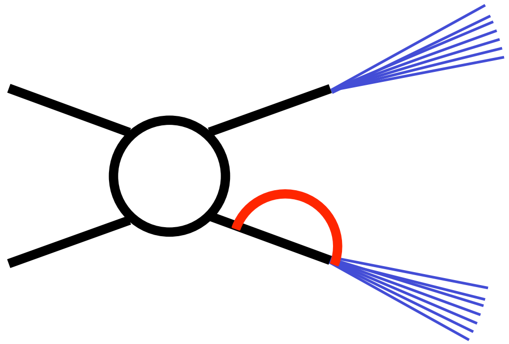
Multi-leg matrix elements fully merged with parton showers (ALPGEN/MLM, SHERPA/CKKW)



Fixed-order calculations (NLO / NNLO, additional resummation of logs…)



Recently: NLO+PS matching



Current work: full merging at NLO!

OVERVIEW

¶ HISTORY OF JETS, AND BASIC CONCEPTS

¶ JETS AT HERA, TEVATRON etc. – AND WHAT DID WE LEARN?
- Jet measurements
- The strong coupling
- PDFs
- …

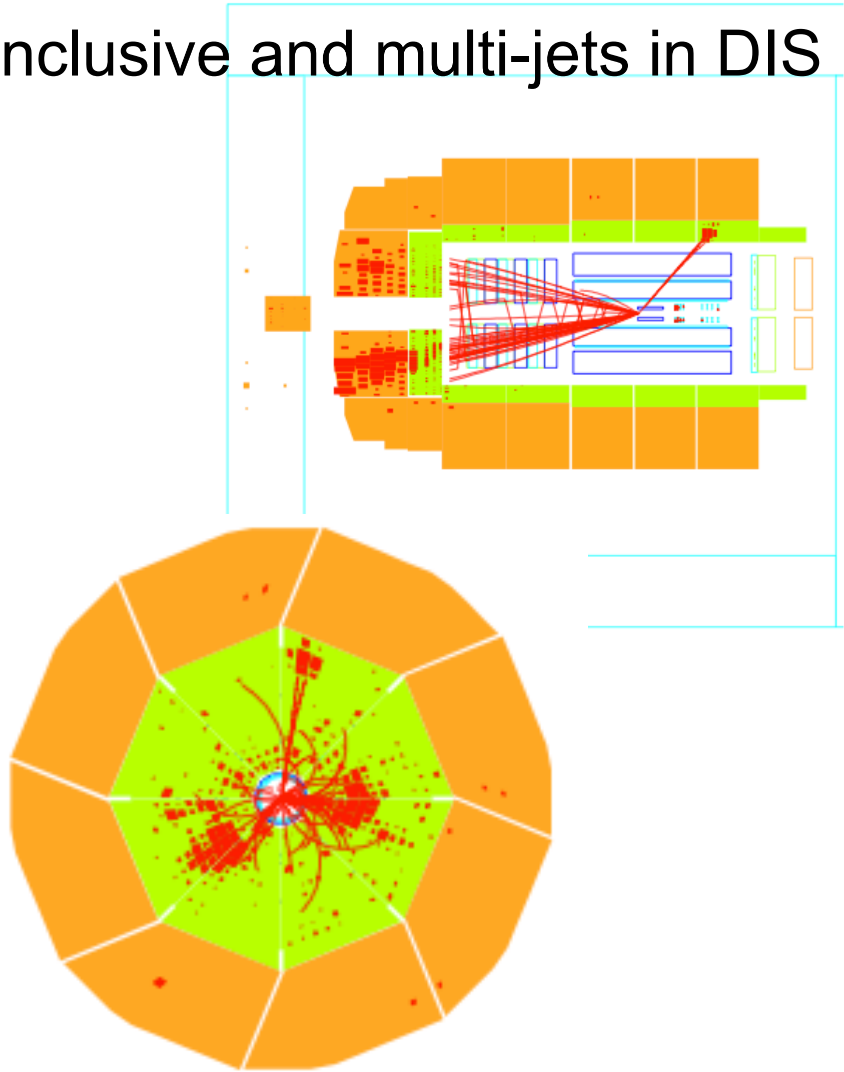
Focus on hadron-beam machines!

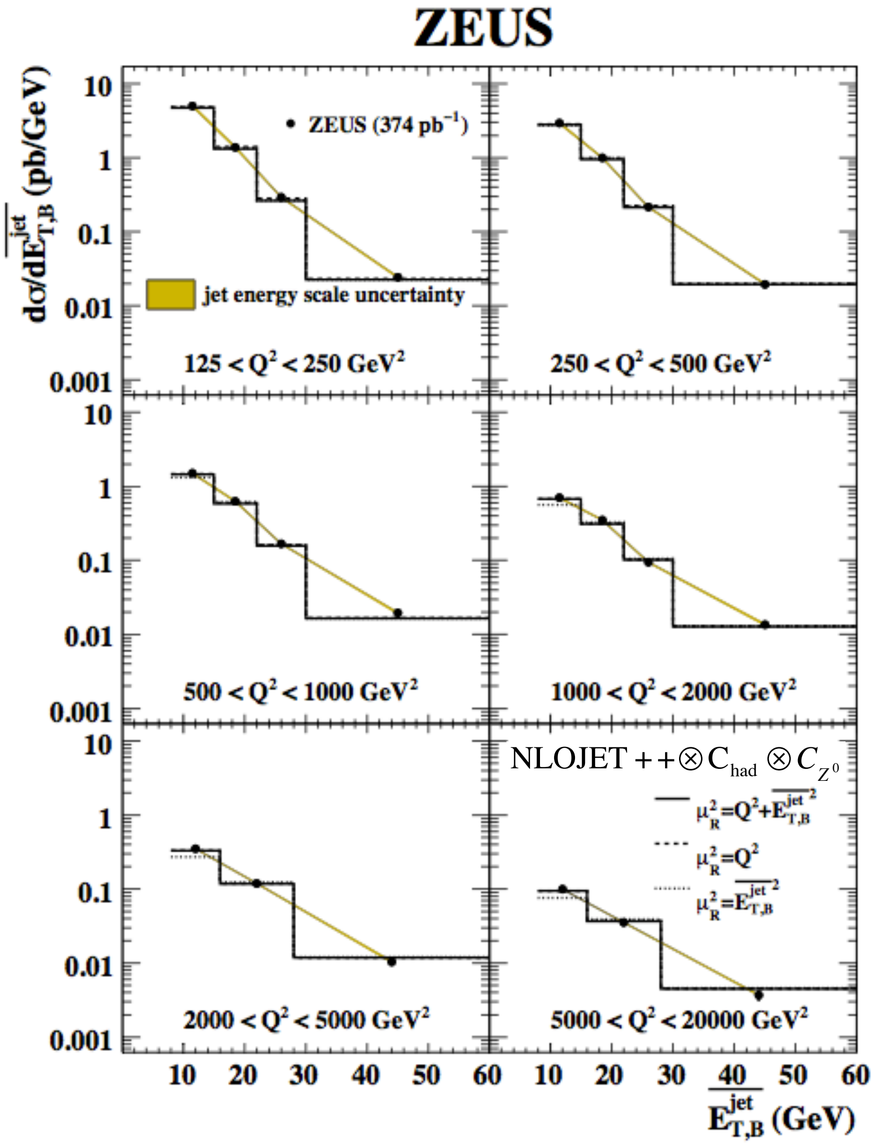
¶ JETS AND QCD AT THE LHC

¶ JETS, NEW CONCEPTS AND NEW PHYSICS

JETS AT HERA

Inclusive and multi-jets in DIS

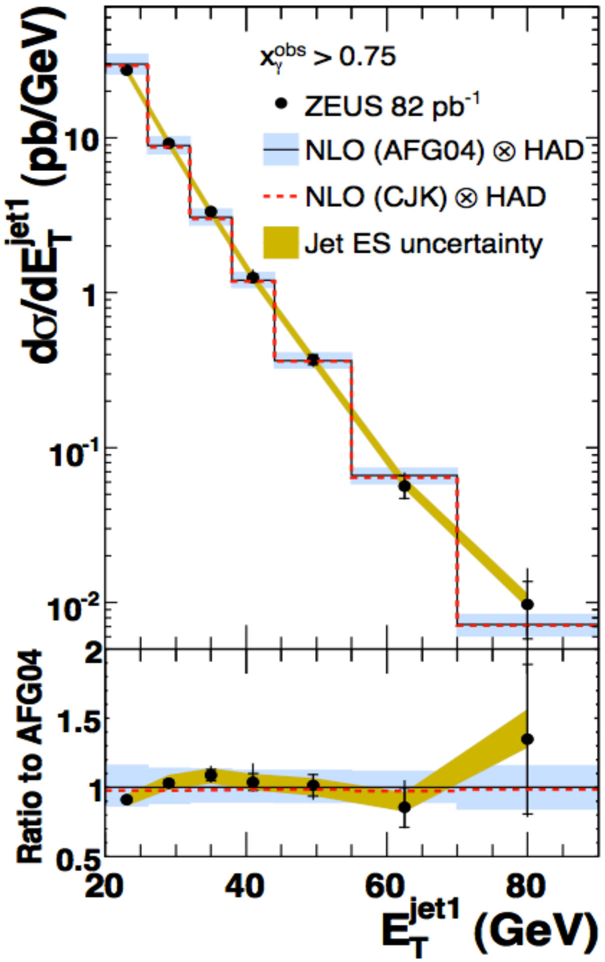


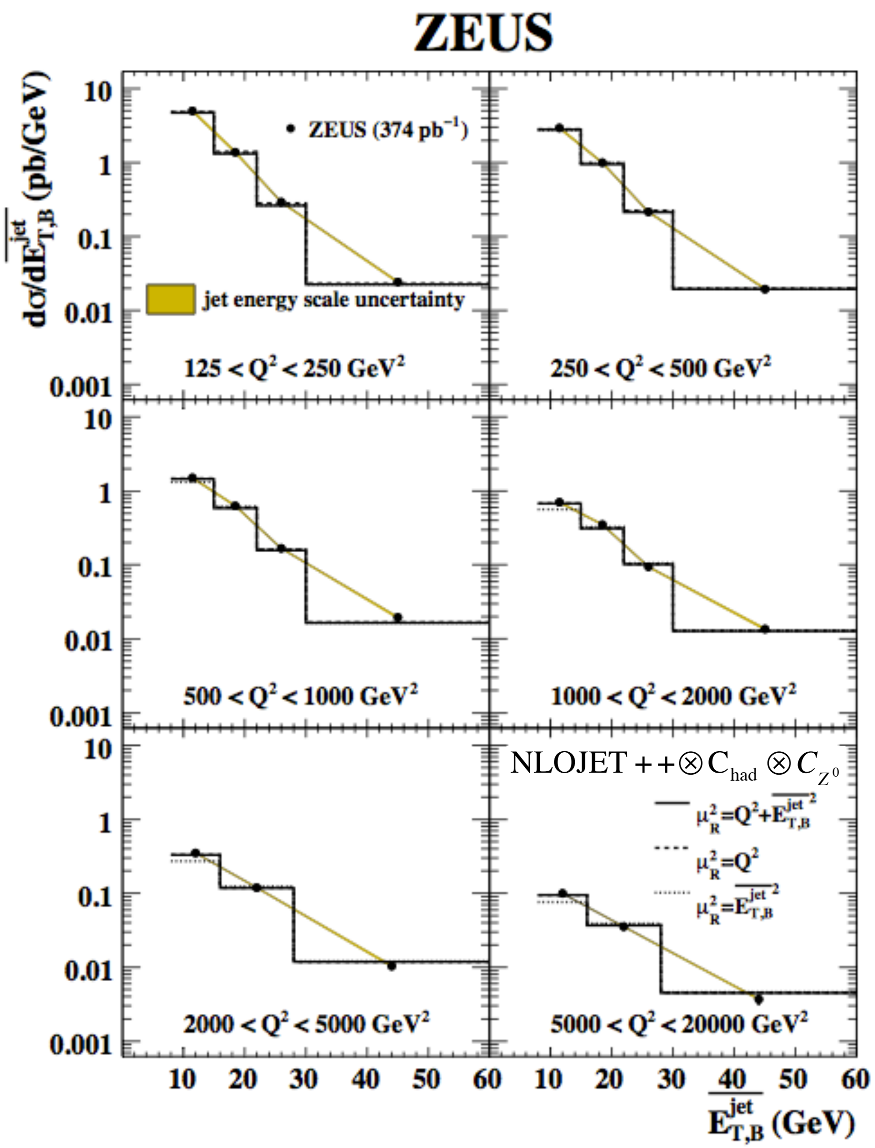


- Description by NLO QCD at the level of 5%; theory uncertainty often dominant.
- Significant influence on strong coupling and PDFs. Energy scale: 1-2%!

JETS AT HERA

…and photoproduction …





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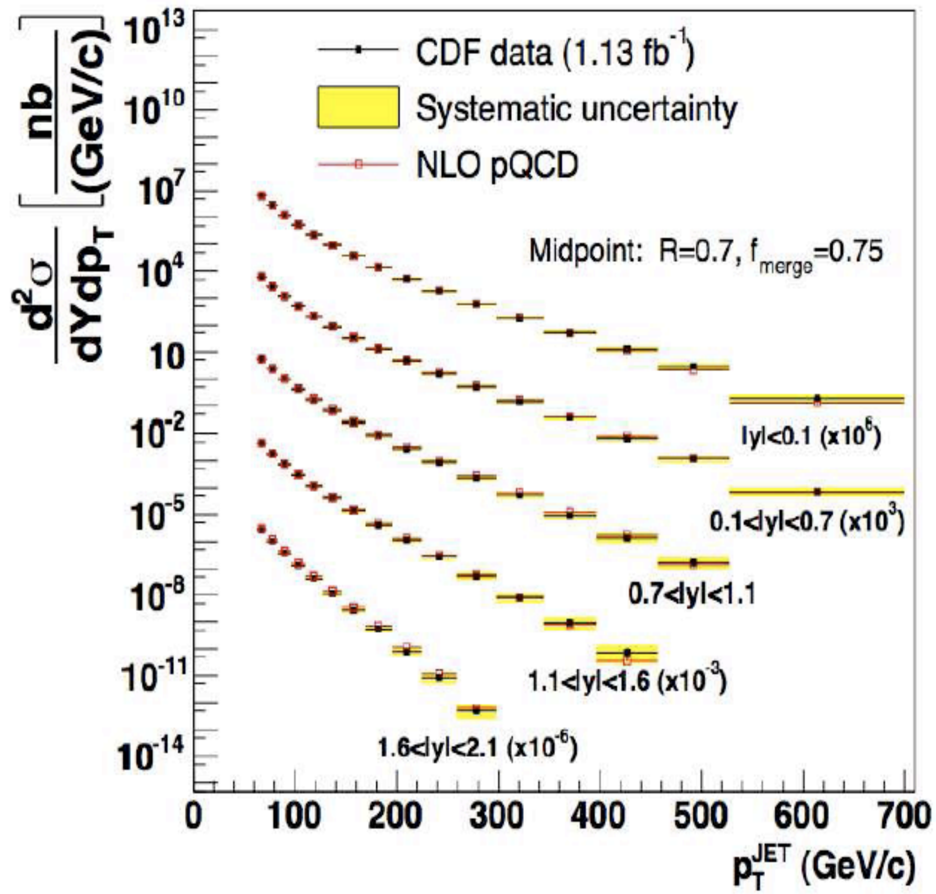
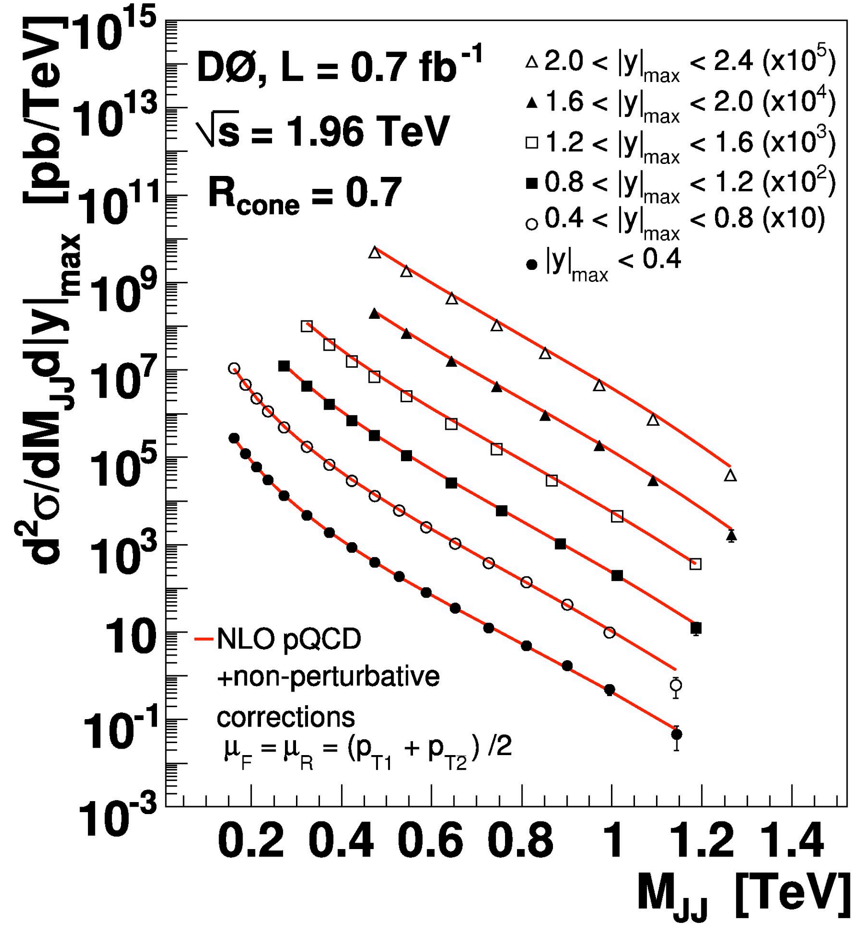
JETS AT THE TEVATRON

Measuring jet E_T up to 600 GeV and dijet masses to 1.3 TeV





- Nice description by NLO QCD, larger (exp.) uncertainties (energy scale)
- Many more results available – cannot show here …

THE GLOBAL PICTURE

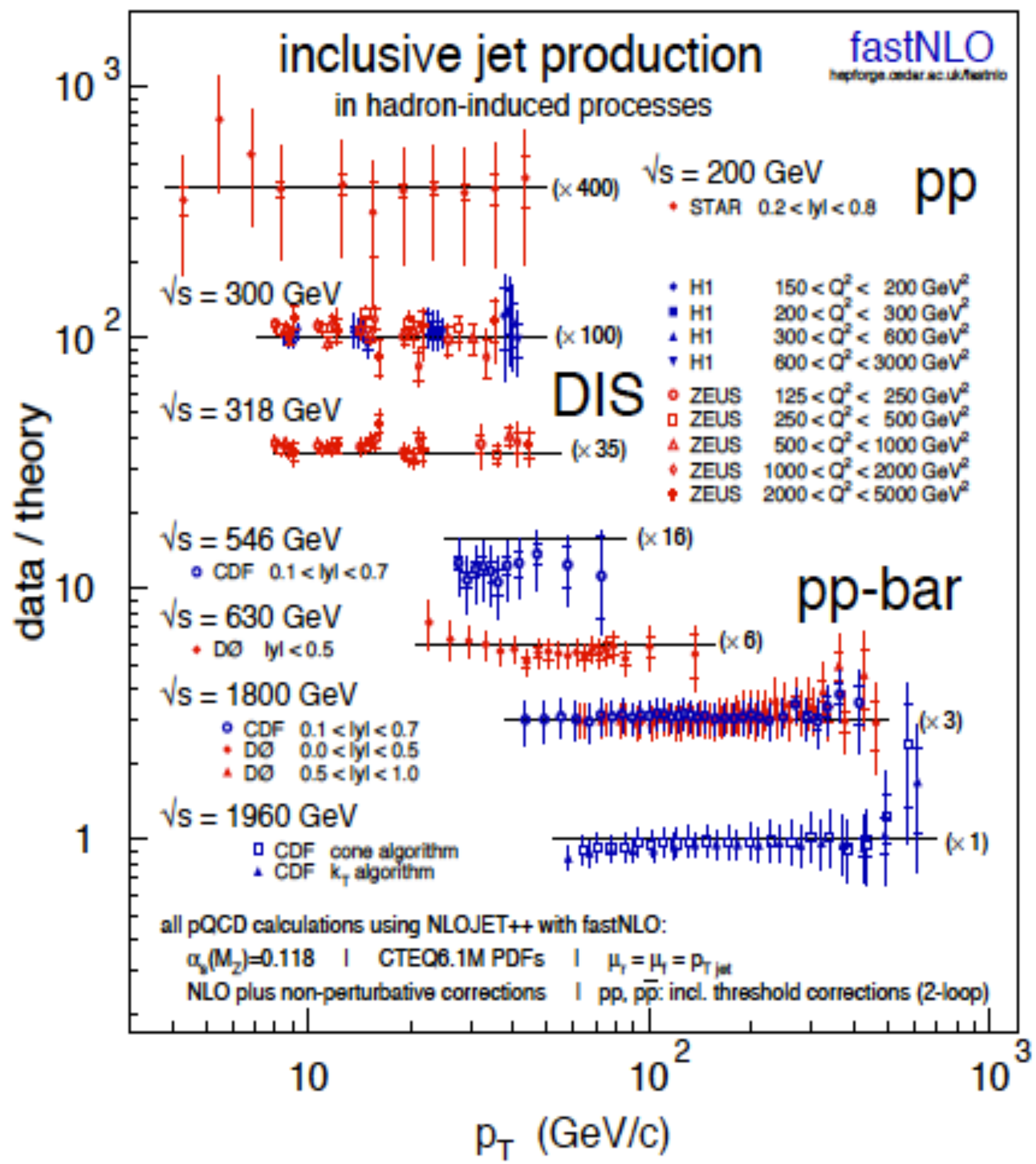
Putting things together

Summary on jets production
in hadron collisions

- with transverse energies from 5 to 600 GeV.
- from different colliders:
  pp, ppbar, ep
  (would be nice to add e^+e^-/2photon data, HERA PHP, …)
- simultaneously described by ONE NLO calculation with ONE PDF set on the level of 10%.

➔ Excellent test of pQCD.
Great success !!!

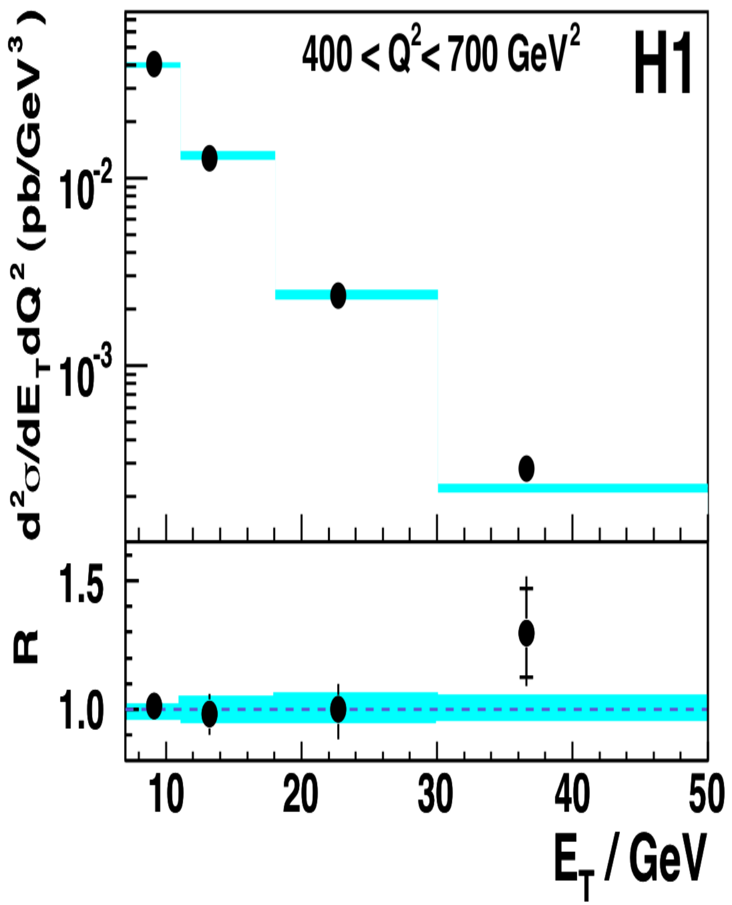
- Hopefully soon: LHC data points!
- And more detailed tests?

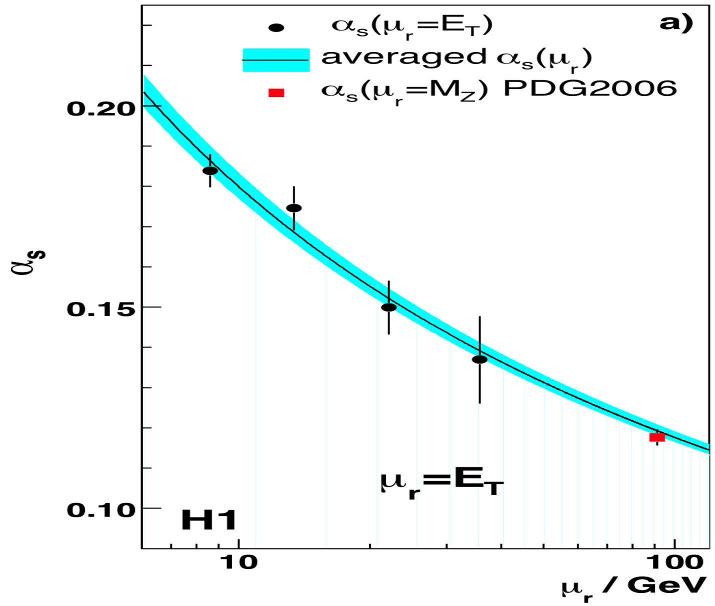


THE STRONG COUPLING

Jet access to the central QCD parameter - HERA

$$\left.\frac{d\sigma}{dA}\right|_{data} \Leftrightarrow \left.\frac{d\sigma(\alpha_S(M_Z))}{dA}\right|_{NLO} = C_1 \cdot \alpha_S(M_Z) + C_2 \cdot \alpha_S^2(M_Z)$$

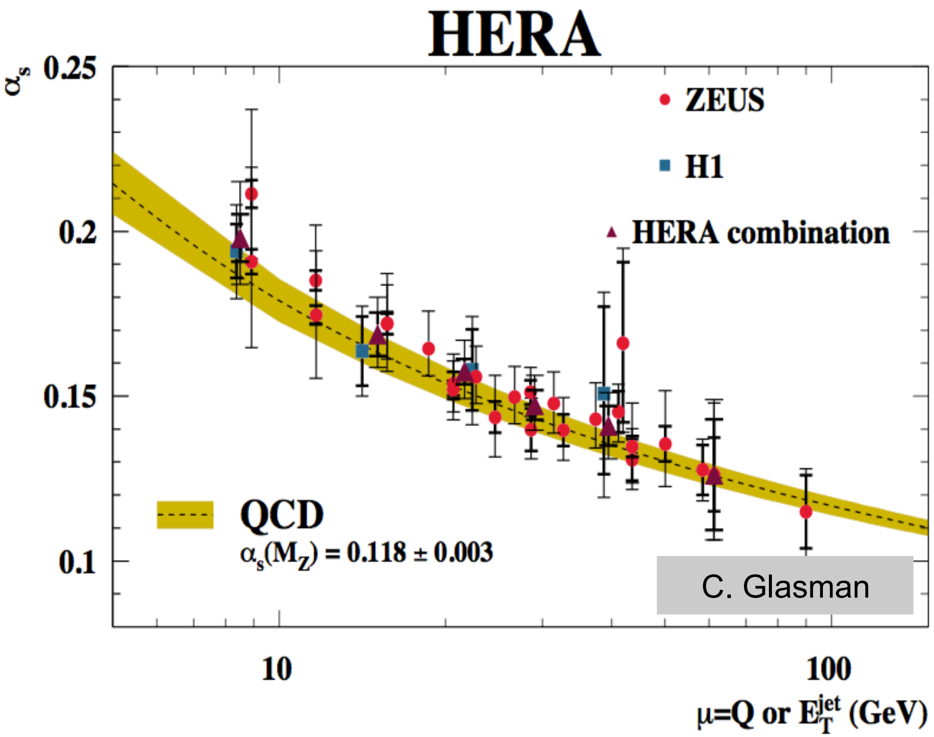


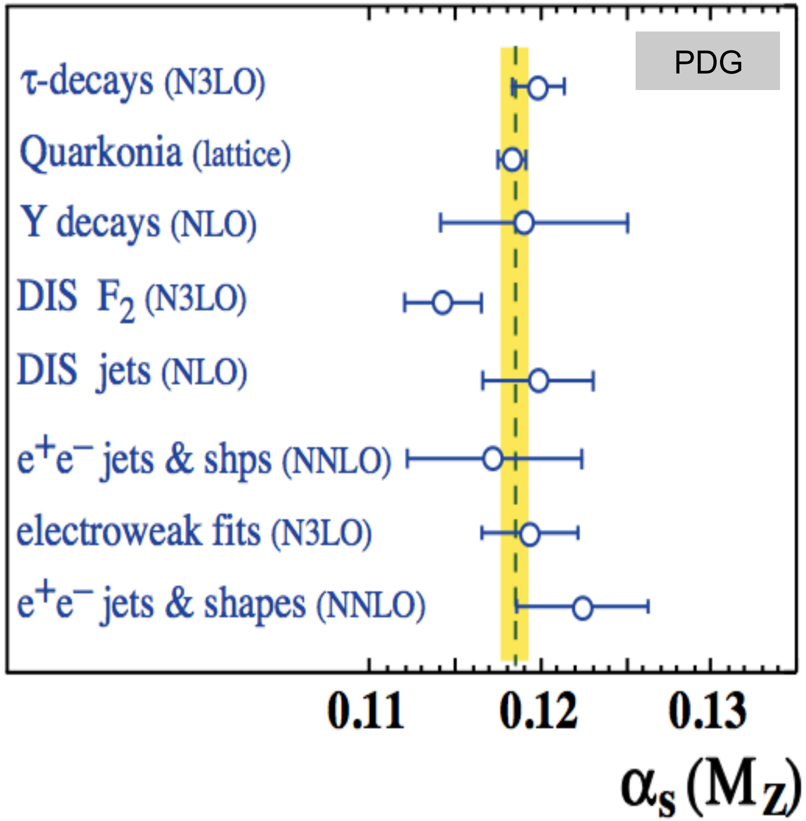


- Each cross section gives one value for α_S.
- Demonstration of running of coupling.
- Combination of measured value to one $\alpha_S(M_Z)$.
- Or simultaneous fit to several data points.

THE STRONG COUPLING

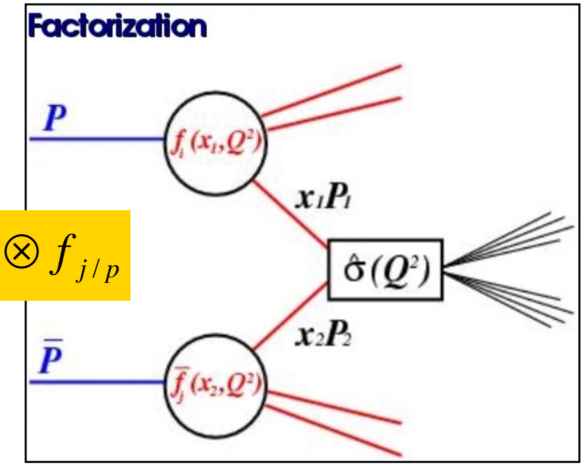
Results and the global picture



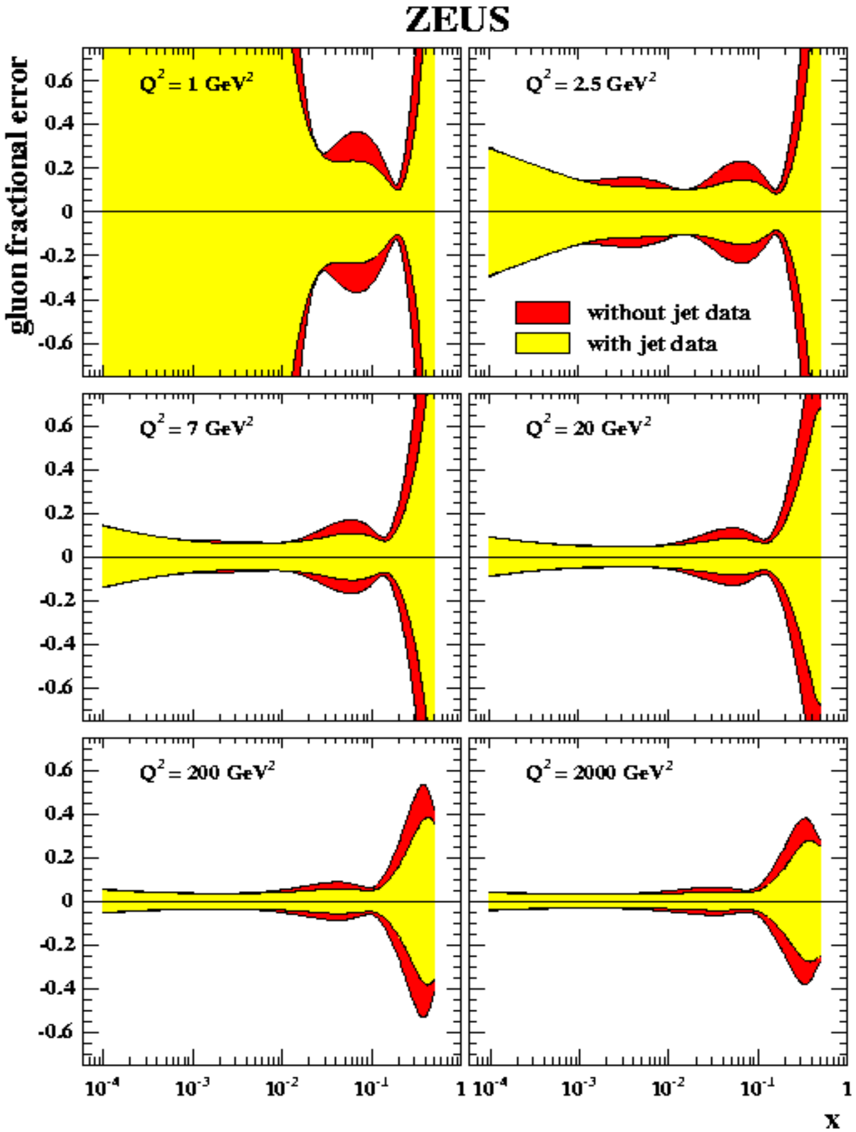


- Consistent values from different machines, energy scales and processes!
- Consistent picture of QCD, QCD as a precision theory! $\alpha_S = 0.1184 \pm 0.0007$

JETS AND THE PDFs



$$\sigma = \sum_{ij} f_{i/p} \otimes \hat{\sigma}_{ij} \otimes f_{j/p}$$



In global PDF fits, jet final states can severely constrain gluon density at medium / high x.

– Example: ZEUS jets fit (2005): Shown is improvement in gluon precision through usage of jet final states (DIS+PHP)

Future: PDF constraints from EW precision observables like W or Z cross sections or ratios:

– Example W charge asymmetry

OVERVIEW

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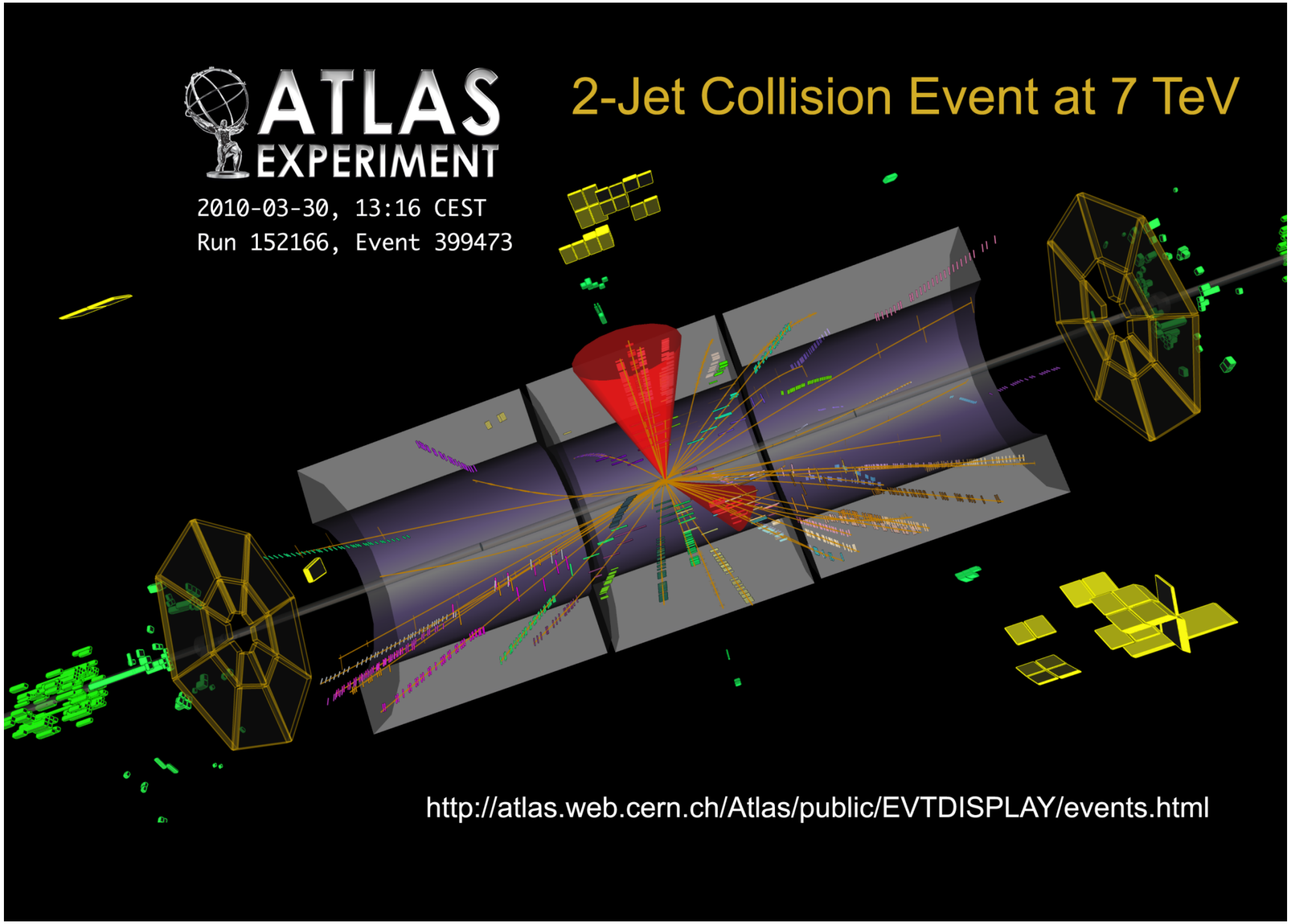
¶ JETS AND QCD AT THE LHC
- Jets at the LHC
- Dijets and azimuthal decorrelations
- Multijets …

¶ JETS, NEW CONCEPTS AND NEW PHYSICS

JETS AT THE LHC

Probing the Terascale with jets of several TeV!



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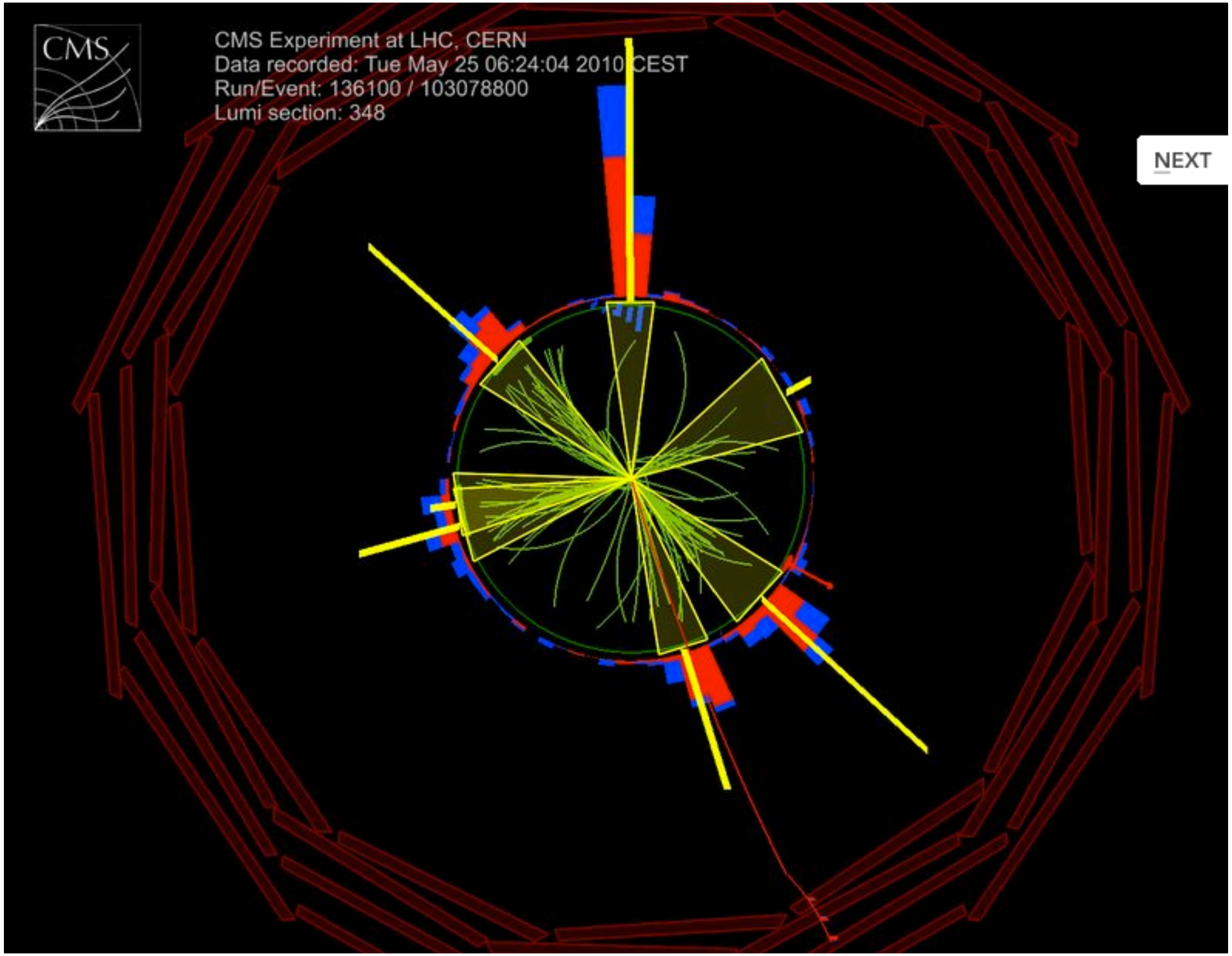
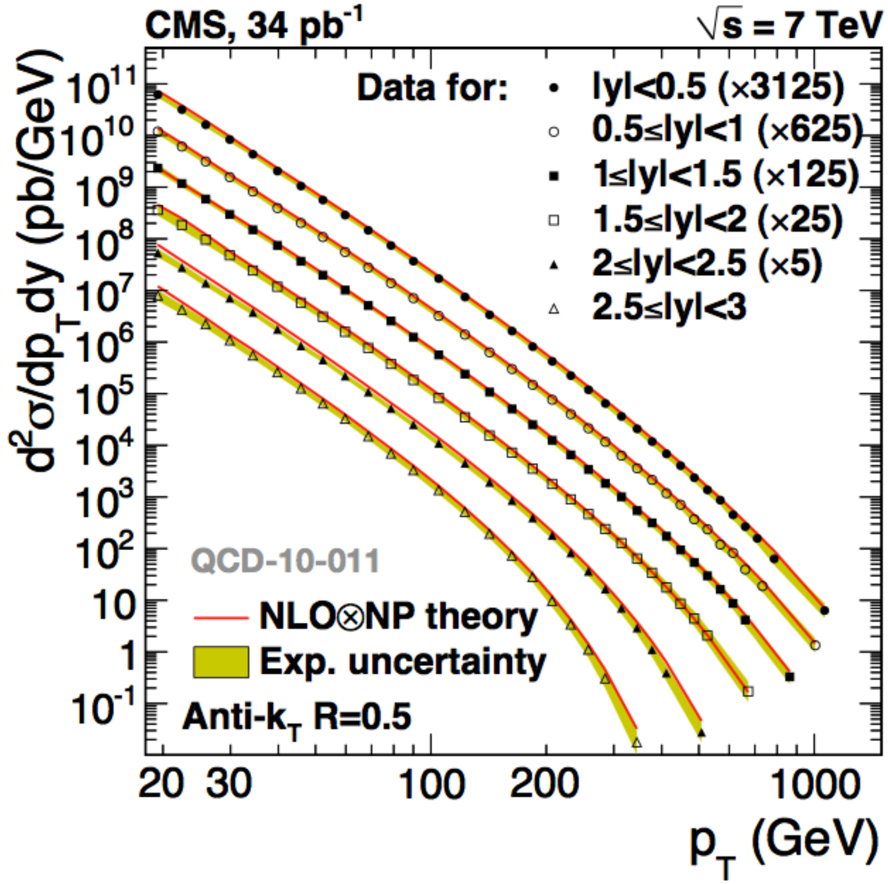
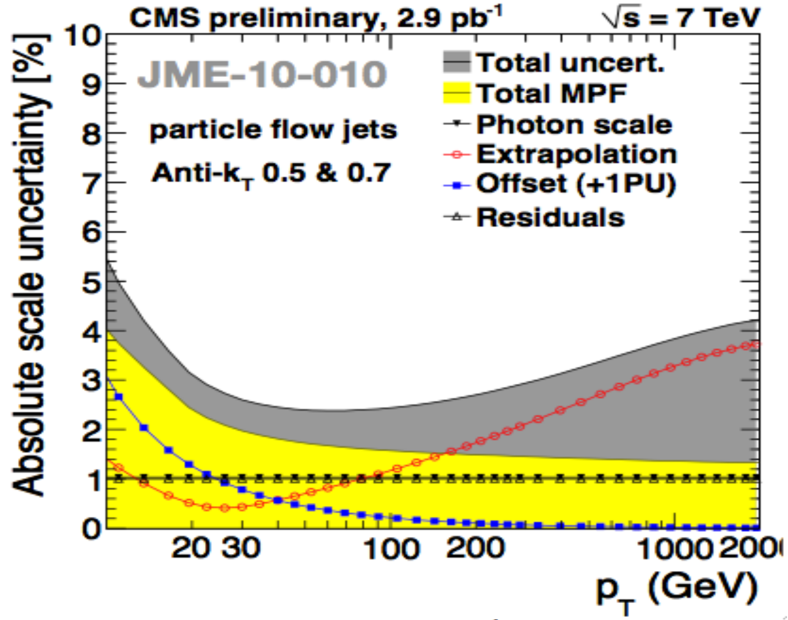
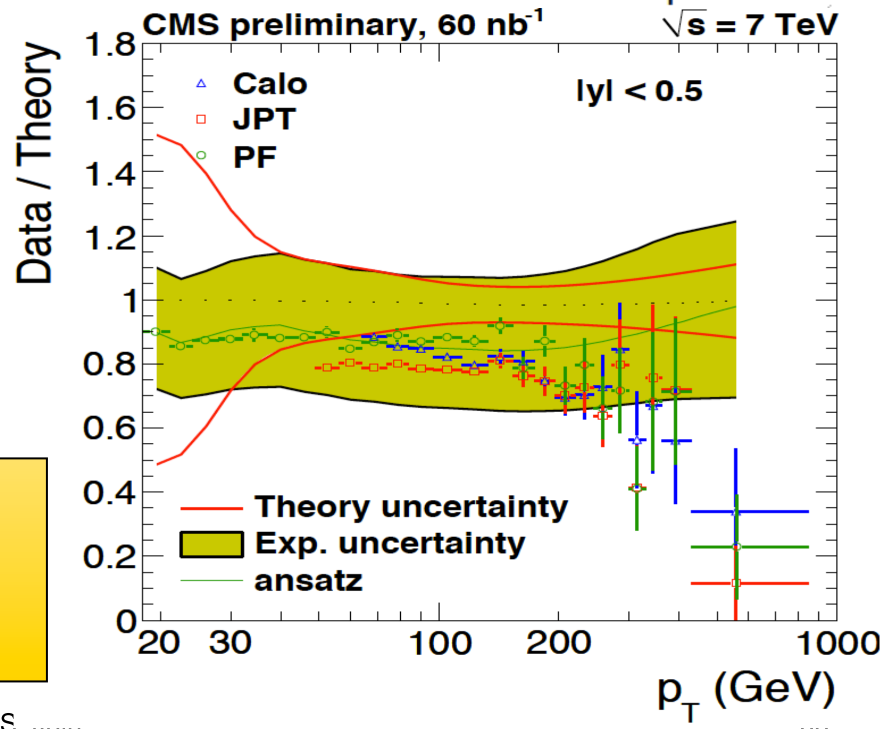


JETS AT THE LHC

Inclusive jet spectra – CMS





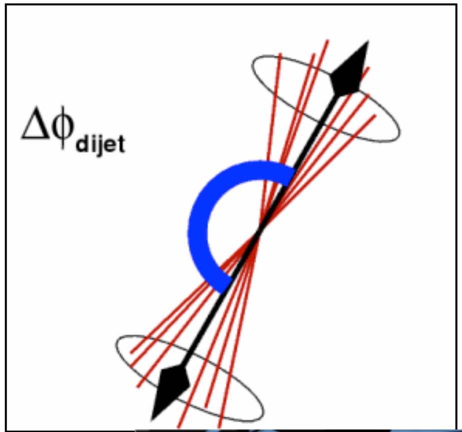


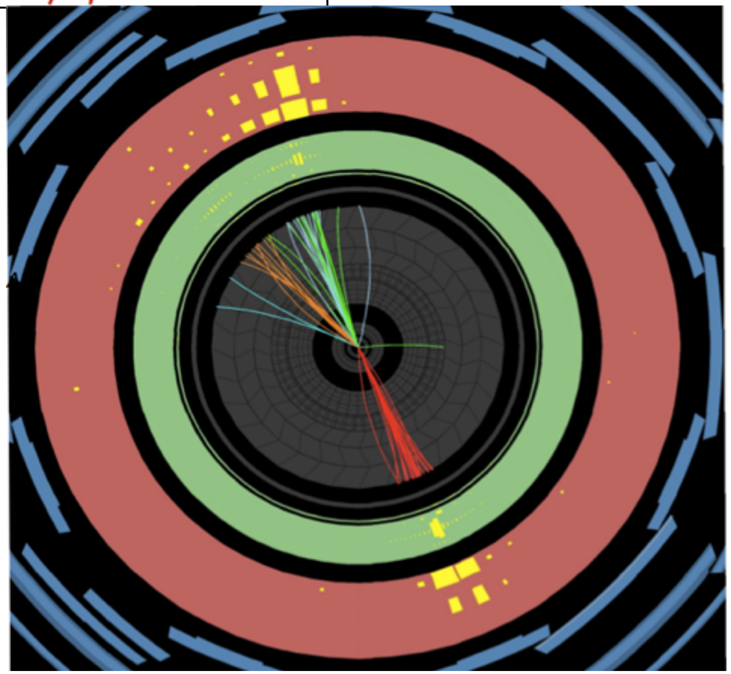
With particle flow jets down to 18 GeV!
JES uncertainty of 3-5%, resolution ~10%.

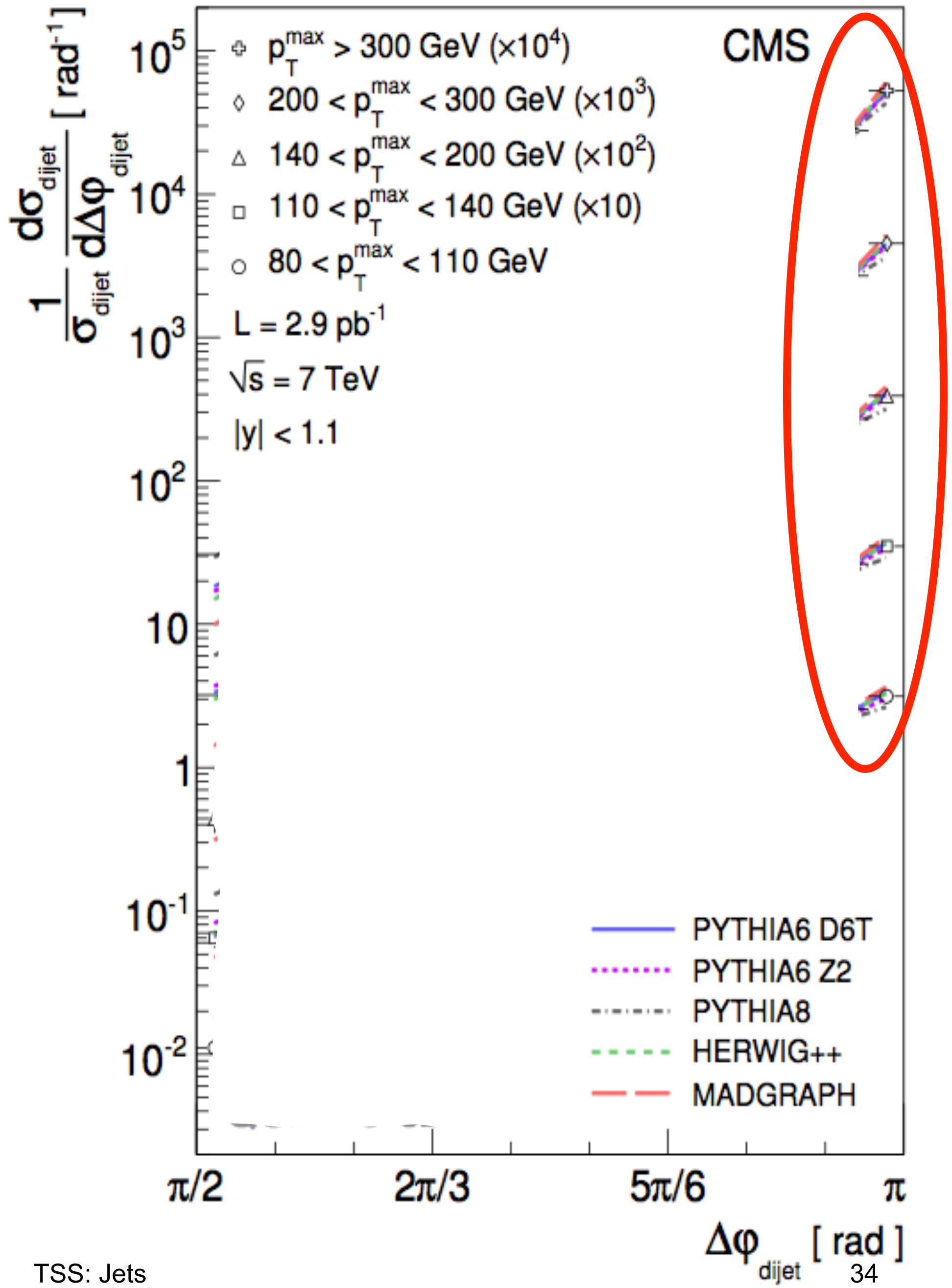
Xsections described over 10 orders !

MULTIJETS

Dijet azimuthal decorrelation







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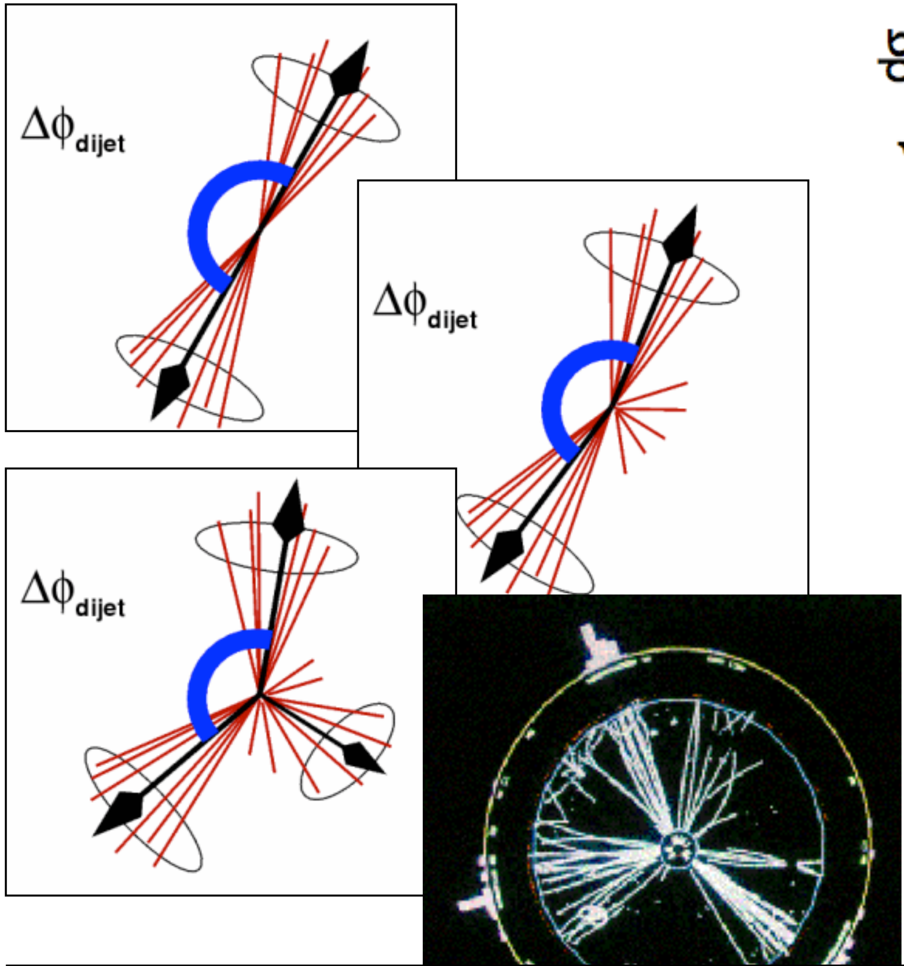

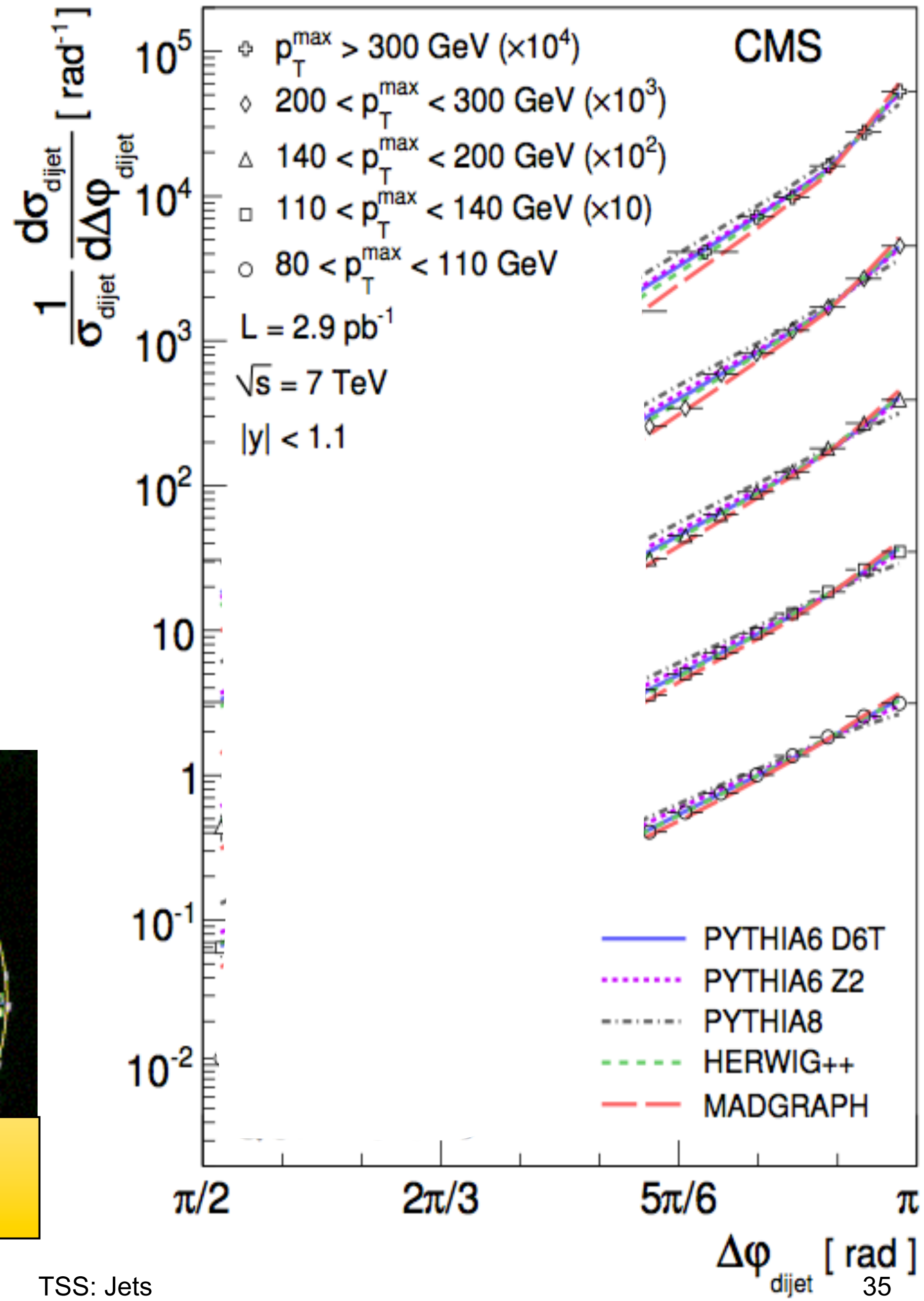

Sensitivity to QCD radiation, understanding is fundamental for new physics searches.

MULTIJETS

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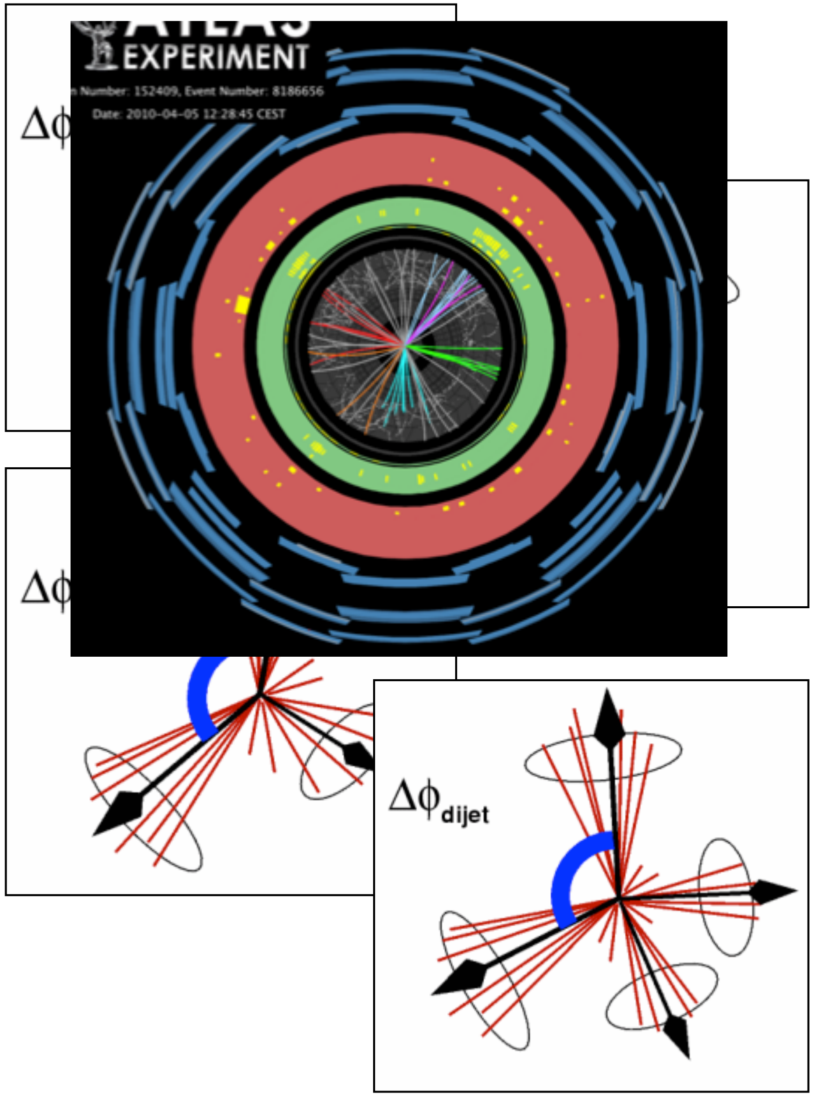
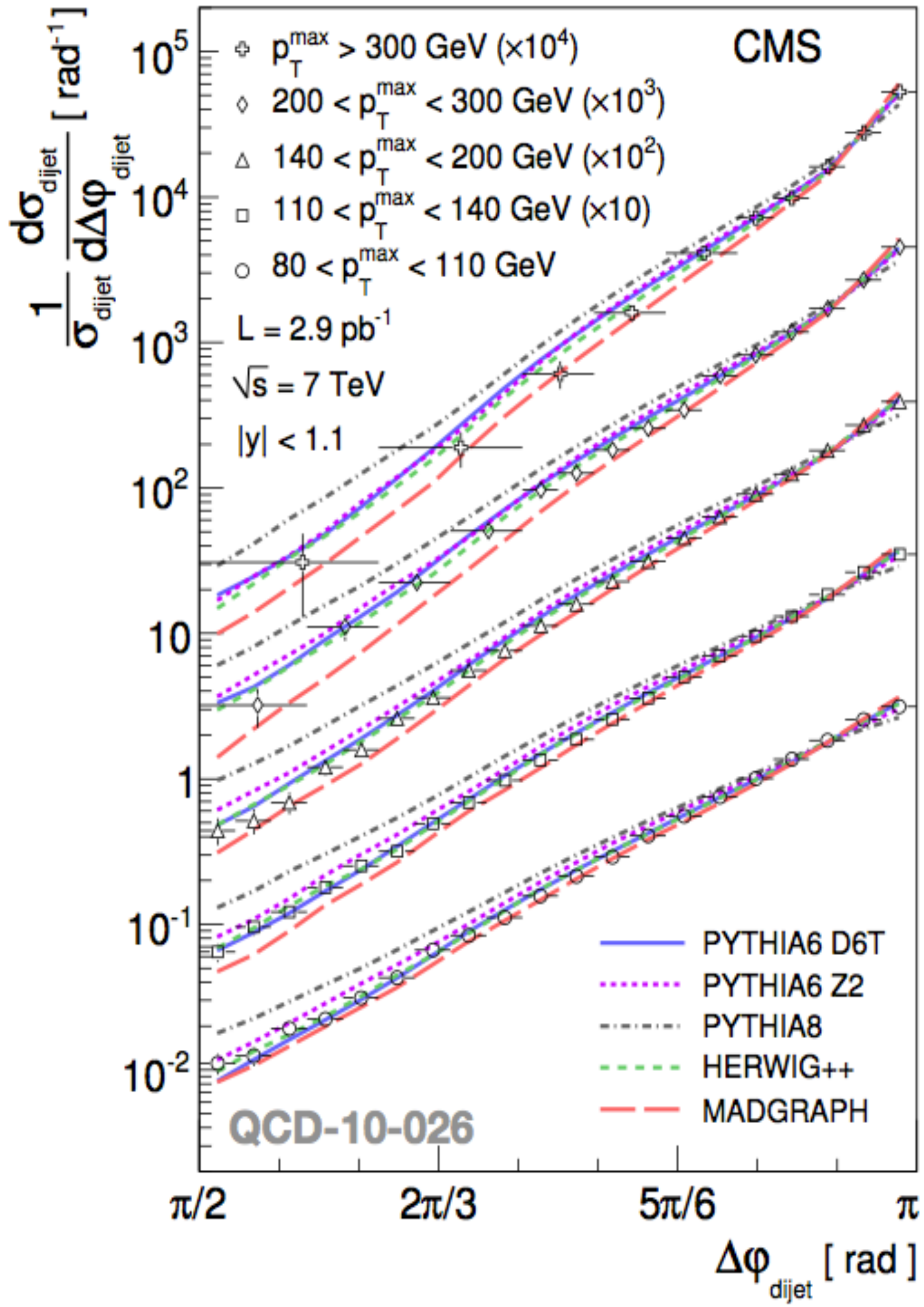
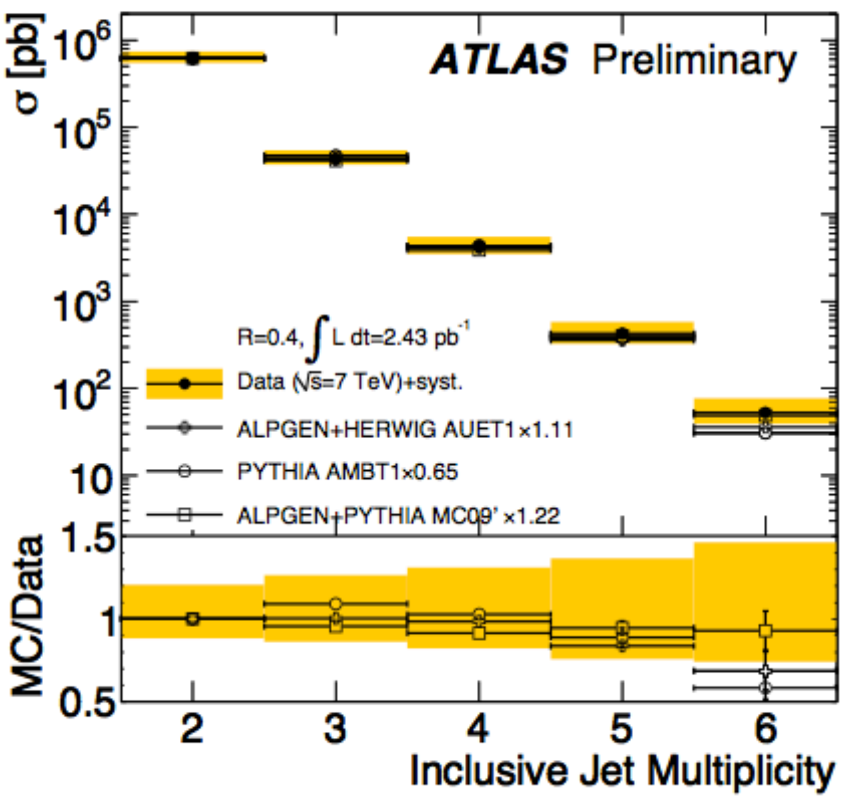
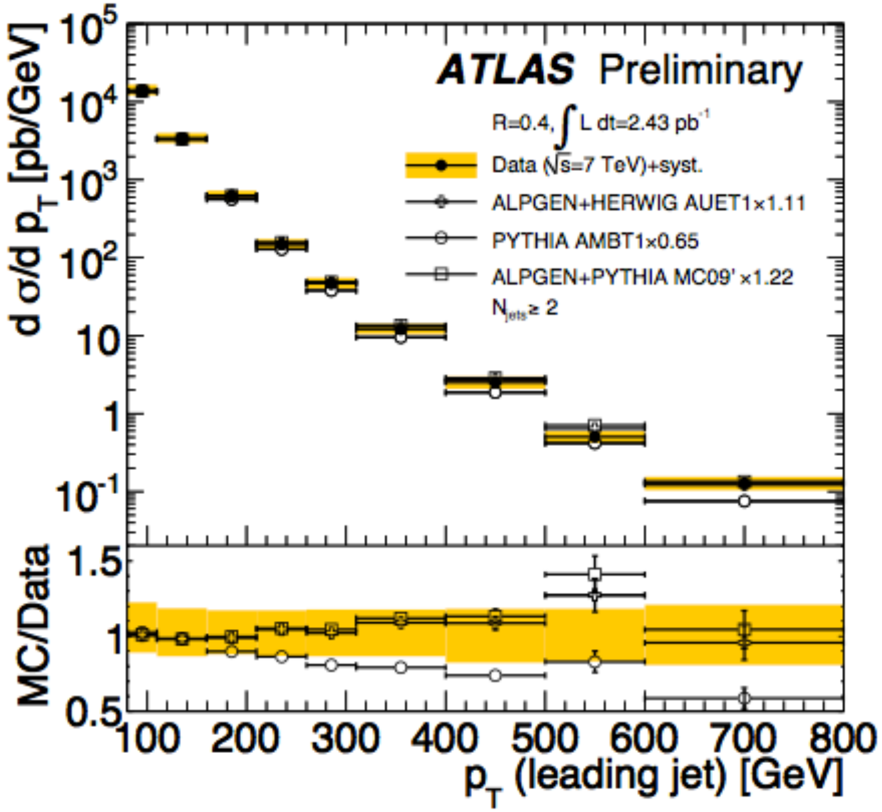




MULTIJETS

From ATLAS – up to 6 jets! $p_{T,lead}$ > 80 GeV

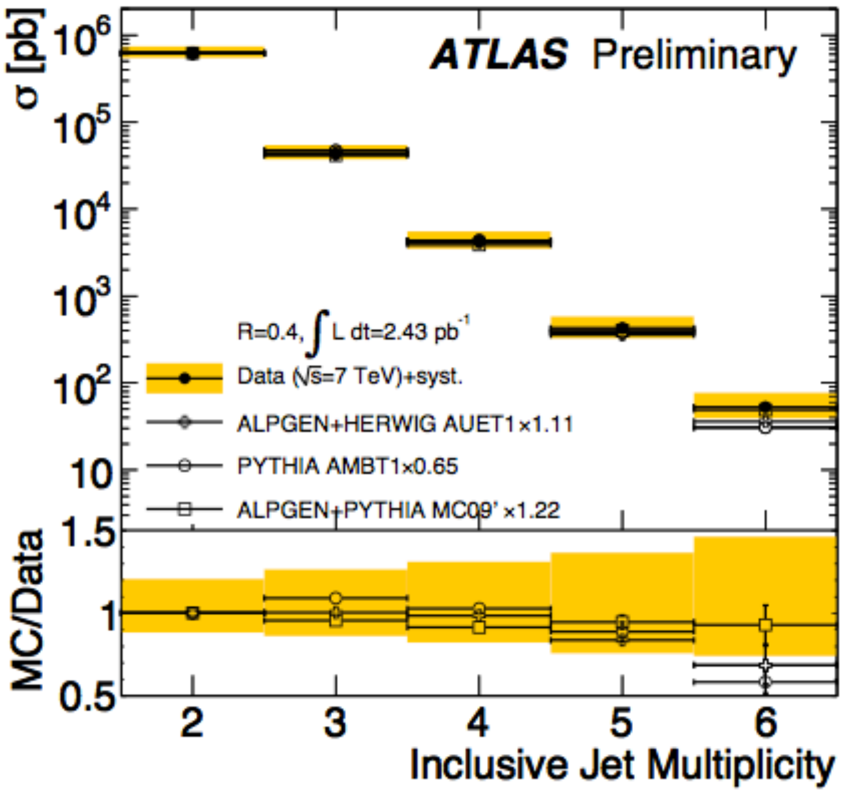


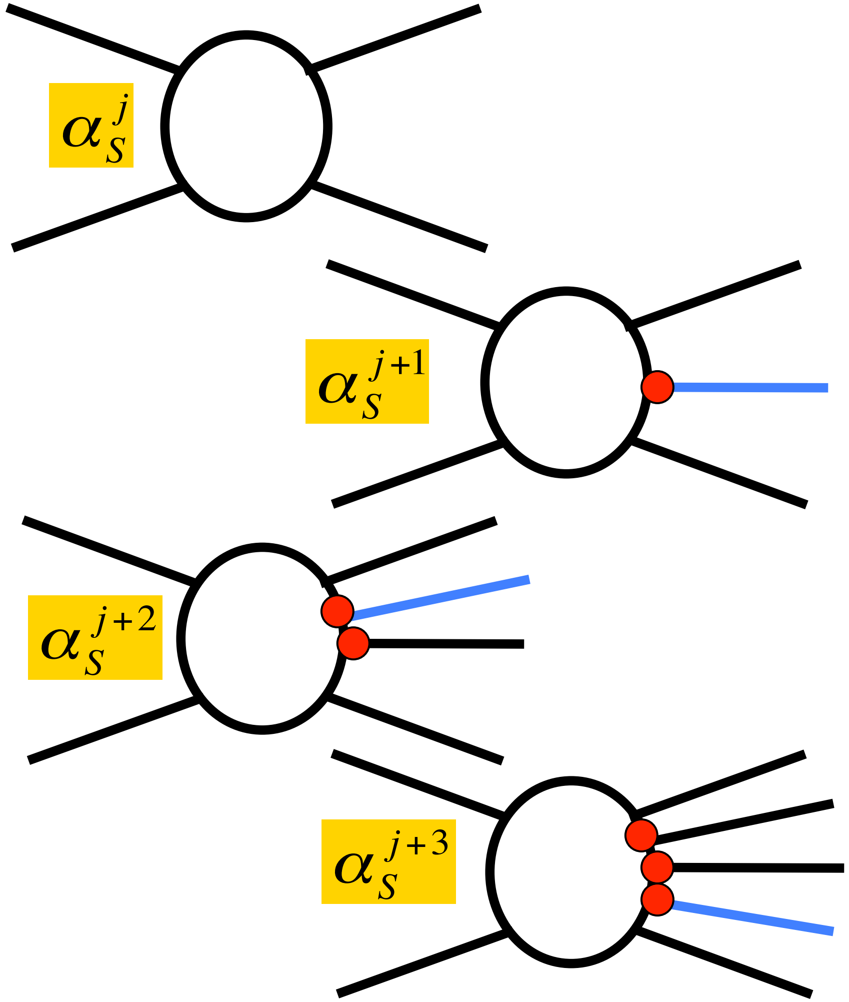


Cross section uncertainty 20-40%, decent description by QCD.

MULTIJETS

Expansion of cross section: $\sigma = \sum \alpha_S^n \cdot C_n = \alpha_S^0 \cdot C_0 + \alpha_S^1 \cdot C_1 + \alpha_S^2 \cdot C_2 + \ldots$



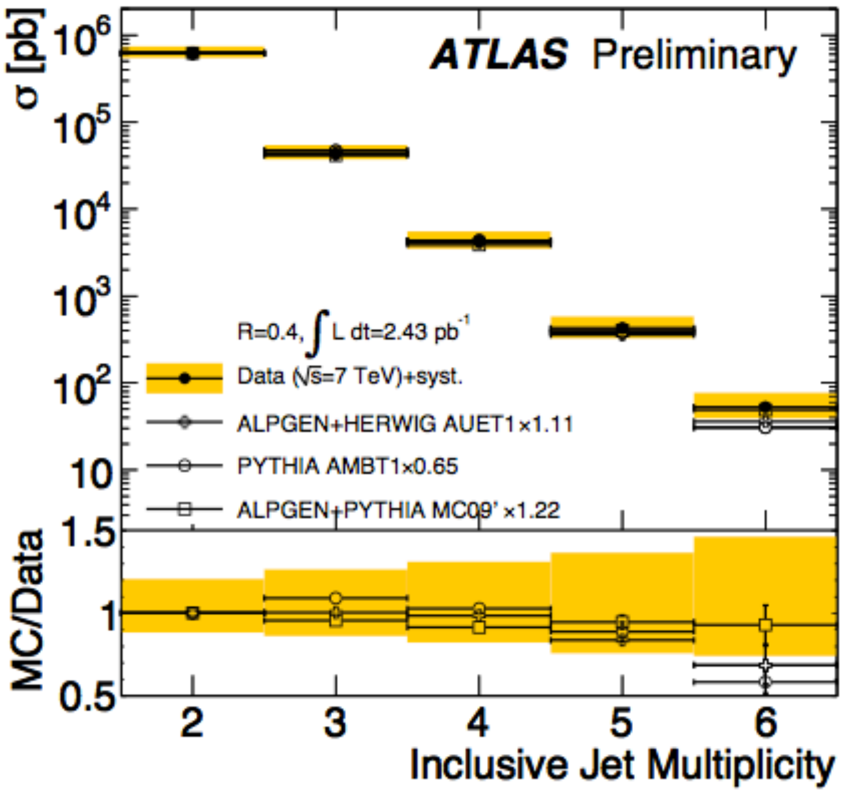


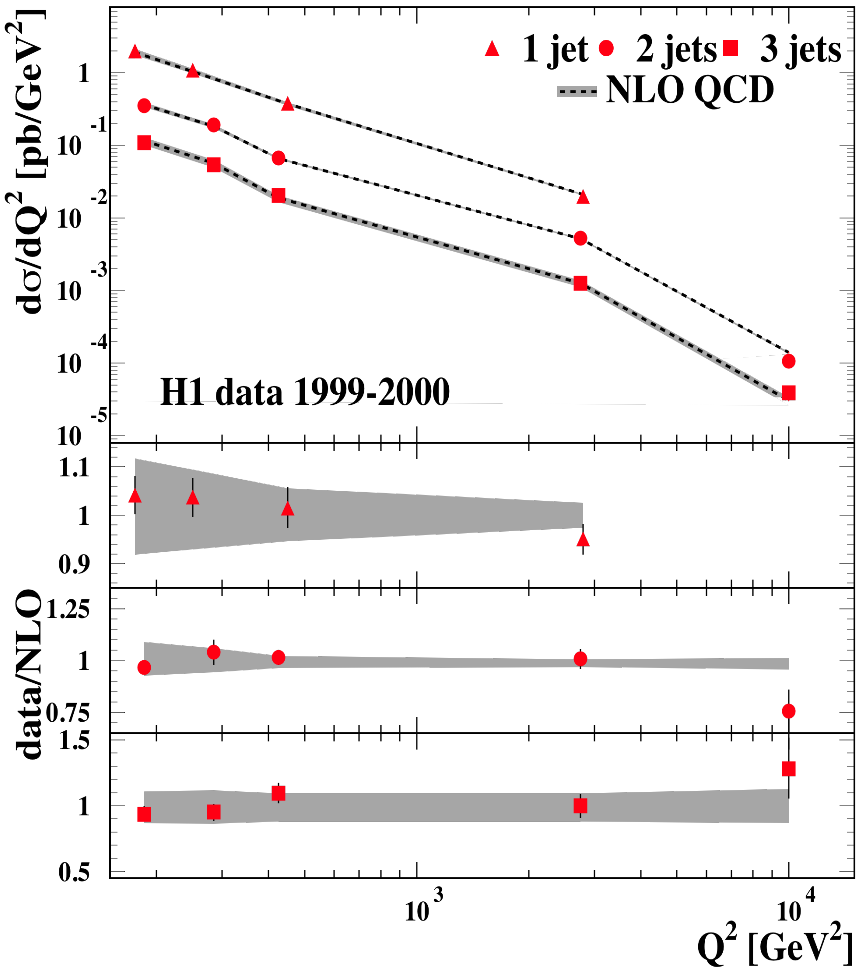
n jets ➔ (n+1) jets ➔ cross section reduced by α_S (modulo phase space)

MULTIJETS

Expansion of cross section:

$$\sigma = \sum \alpha_S^n \cdot C_n = \alpha_S^0 \cdot C_0 + \alpha_S^1 \cdot C_1 + \alpha_S^2 \cdot C_2 + \ldots$$





n jets → (n+1) jets ➔ cross section reduced by α_S (modulo phase space)

OVERVIEW

¶ HISTORY OF JETS, AND BASIC CONCEPTS

¶ JETS AT HERA, TEVATRON etc. – AND WHAT DID WE LEARN?

¶ JETS AND QCD AT THE LHC

¶ JETS, NEW CONCEPTS AND NEW PHYSICS
- Dijet mass spectra
- χ and dijet centrality ratio
- Jet area, jet trimming/pruning/filtering/tagging etc.

JET AND NEW PHYSICS – DIJETS

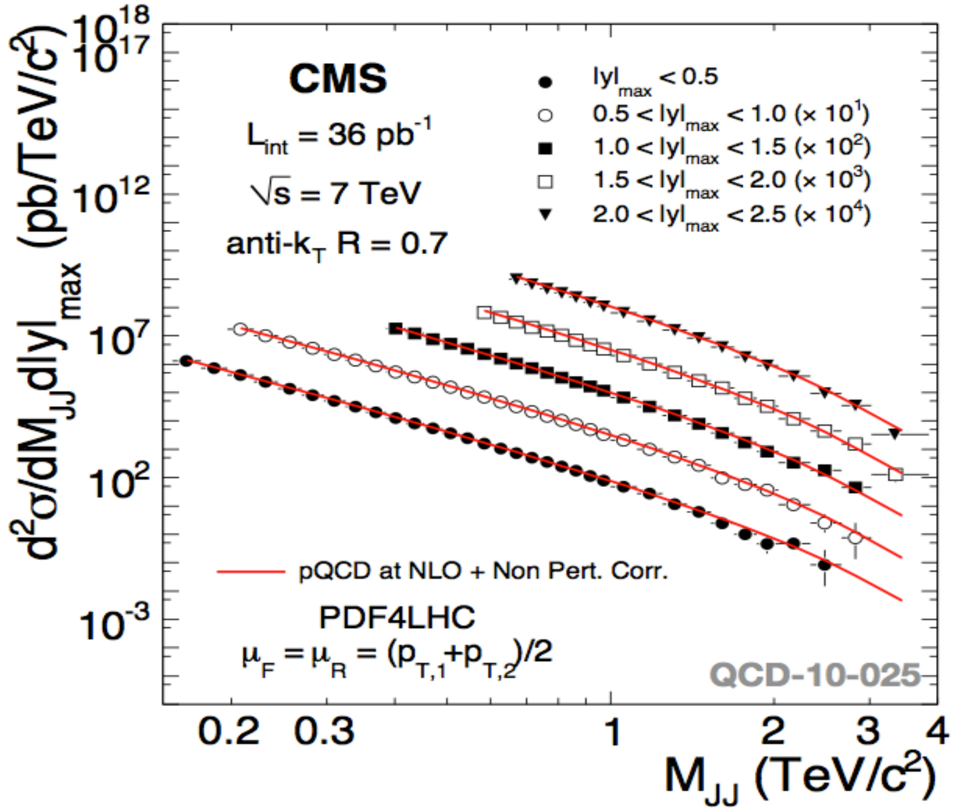
Dijets for new and old physics

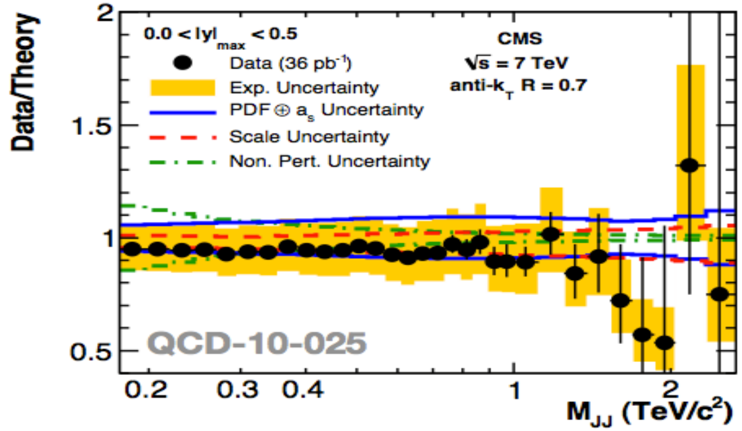
Dijets allow detailed tests of the phase space and of QCD dynamics
- comparison to NLO QCD.

Specific sensitivity for new physics decaying to qqbar
- tests at HERA, Tevatron, …
- so far only limits to new physics models
- but certainly also discovery potential

Observables: dijet mass, χ, centrality ratio (later)

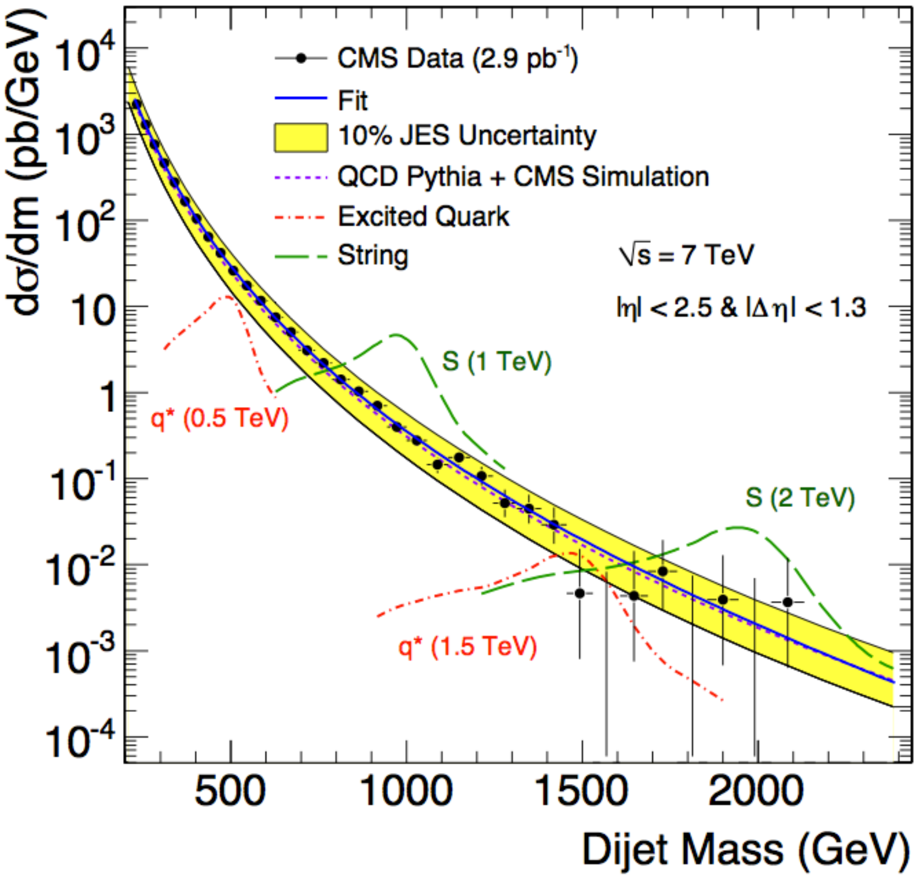
Example CMS: M_{JJ} up to 3.5 TeV
- results compatible with incl. jet findings

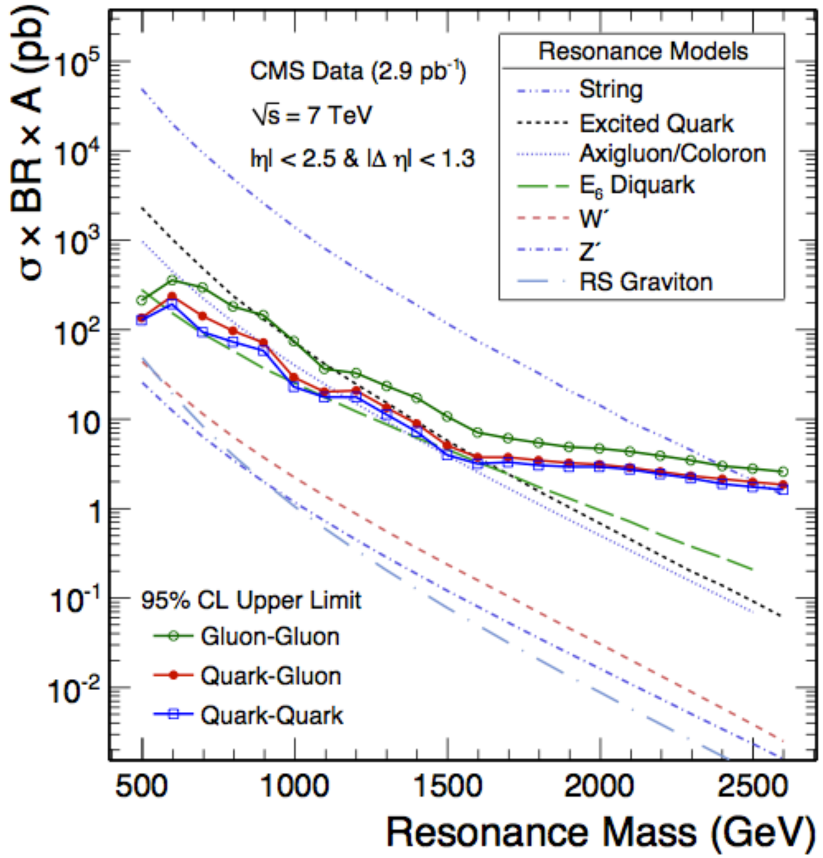




JET AND NEW PHYSICS – DIJETS

Dijet mass spectra

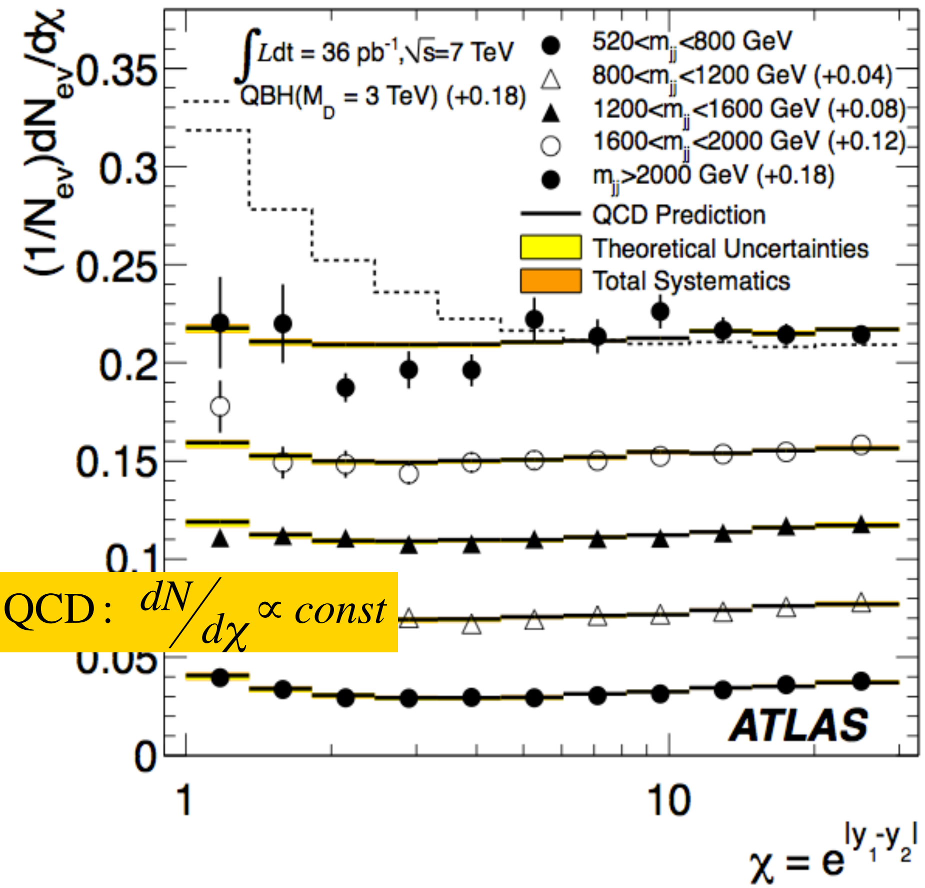




Derive 95% CL limits on resonances masses from comparison of model predictions and 95% limit on measured cross section.

JET AND NEW PHYSICS – DIJETS

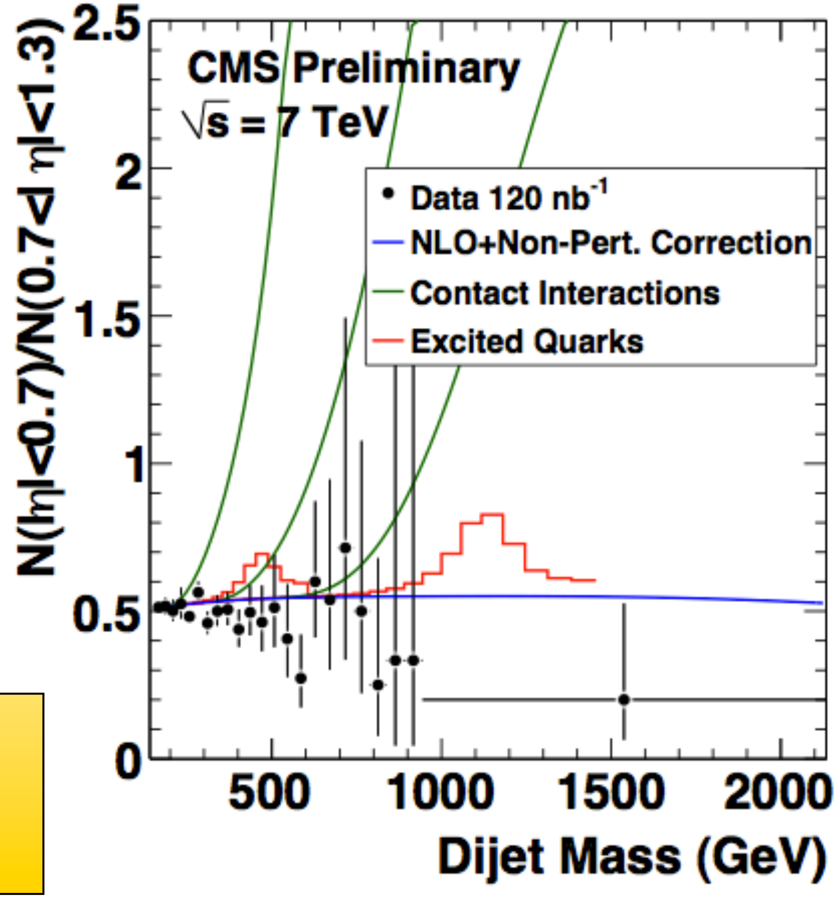
Discovering and interpreting new physics



QCD: $dN/d\chi \propto const$

Dijet centrality ratio: ratio of dijets in central to dijets in non-central region

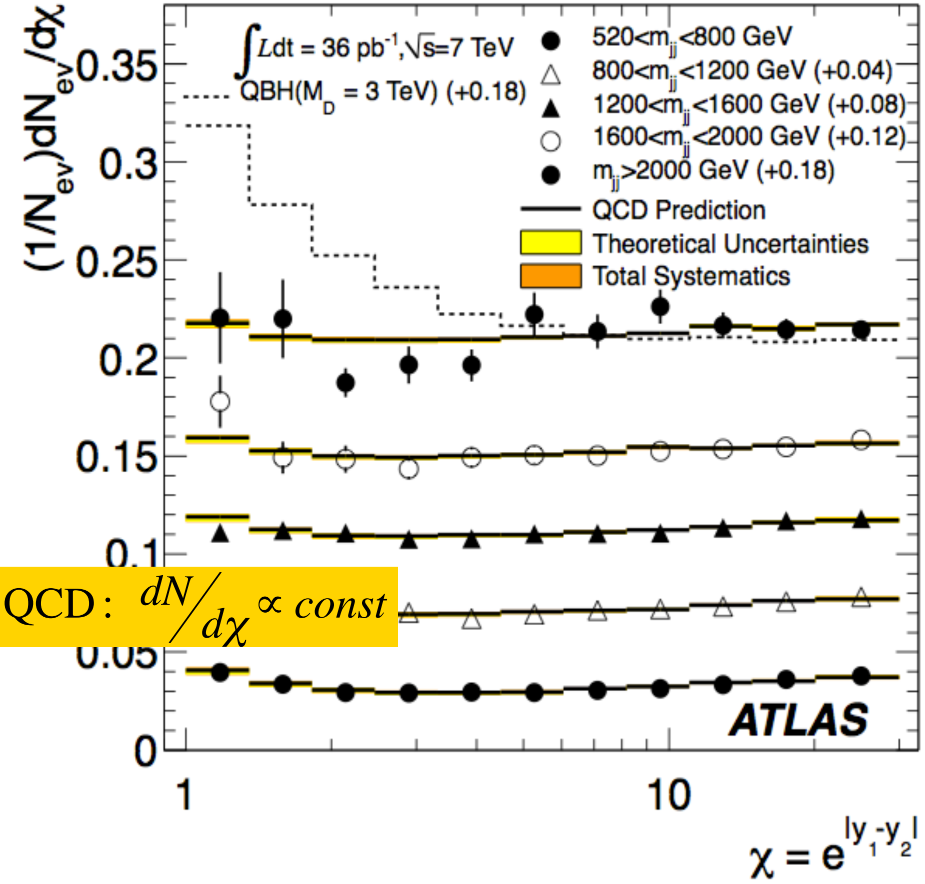
→ Cancellation of uncertainties!!!



- New heavy physics mainly central (χ=1).
- Asymmetry χ and centrality ratio complementary: χ sensitive to spin, centrality ratio to mass

JET AND NEW PHYSICS – DIJETS

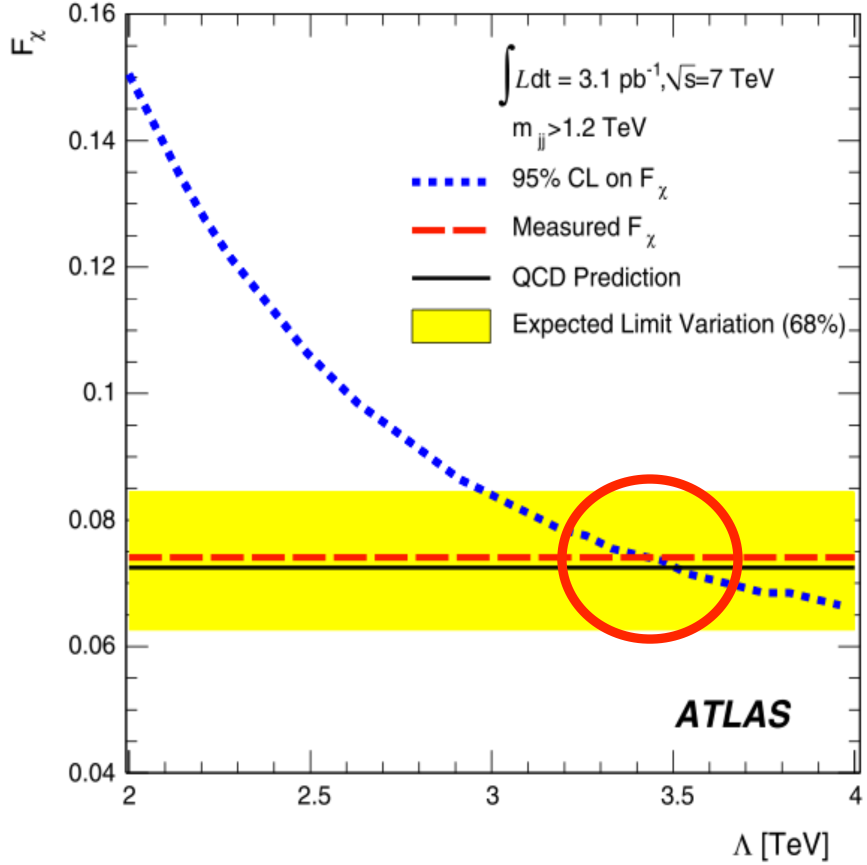
Discovering and interpreting new physics



$$\text{QCD}: \; dN/d\chi \propto const$$

ATLAS (36 pb^{-1}): Λ_{CI} > 6.6-9.5 TeV
CMS (36 pb^{-1}): Λ_{CI} > 5.6 TeV

$$F(\chi) = \frac{\text{events in four highest } \chi \text{ bins}}{\text{events in all } \chi \text{ bins}}$$



JET AND NEW PHYSICS – DIJETS

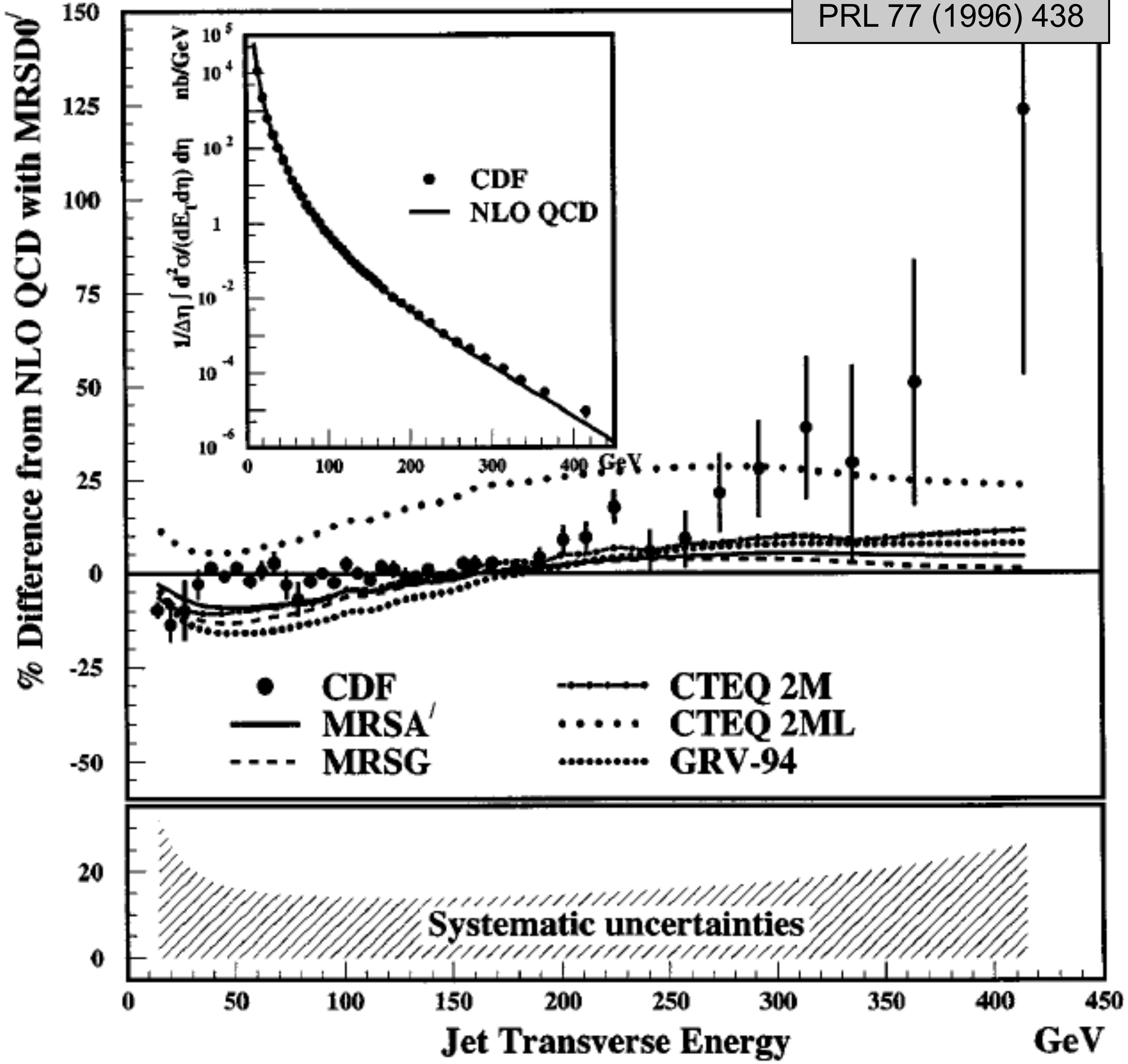
ATLAS limits from resonance searches in dijet distributions

Model and Analysis Strategy	95% C.L. Limits (TeV) Expected	Observed
Excited Quark q^*		
Resonance in m_{jj}	2.07	2.15
$F_\chi(m_{jj})$	**2.12**	**2.64**
Randall-Meade Quantum Black Hole for $n = 6$		
Resonance in m_{jj}	**3.64**	**3.67**
$F_\chi(m_{jj})$	3.49	3.78
θ_{np} Parameter for $m_{jj} > 2$ TeV	3.37	3.69
11-bin χ Distribution for $m_{jj} > 2$ TeV	3.36	3.49
Axigluon		
Resonance in m_{jj}	**2.01**	**2.10**
Contact Interaction Λ		
$F_\chi(m_{jj})$	**5.7**	**9.5**
F_χ for $m_{jj} > 2$ TeV	5.2	6.8
11-bin χ Distribution for $m_{jj} > 2$ TeV	5.4	6.6

JET AND NEW PHYSICS

A warning from the past …

PRL 77 (1996) 438



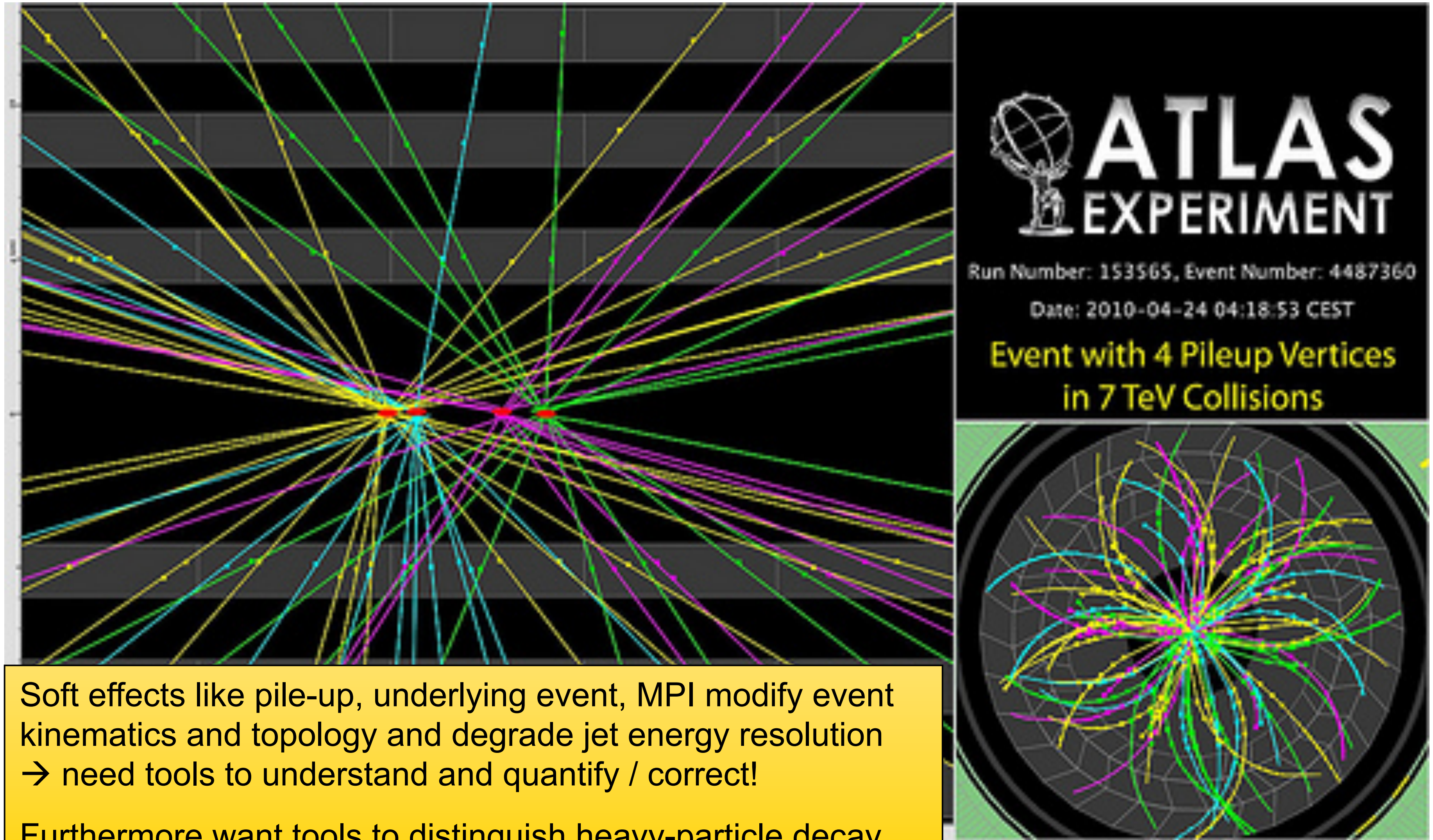
Possible explanations:
quark substructure,
compositeness,
contact interactions, …

Later explained in terms of re-definition of gluon density of the proton.

Don't see new physics where it is not;
don't hide new physics in re-parametrisation of old …

NEW CONCEPTS FOR JETS

The jet area, and trimming, pruning, filtering, tagging etc.



Soft effects like pile-up, underlying event, MPI modify event kinematics and topology and degrade jet energy resolution
→ need tools to understand and quantify / correct!

Furthermore want tools to distinguish heavy-particle decay jets from ordinary QCD jets.

NEW CONCEPTS FOR JETS 1

The jet area

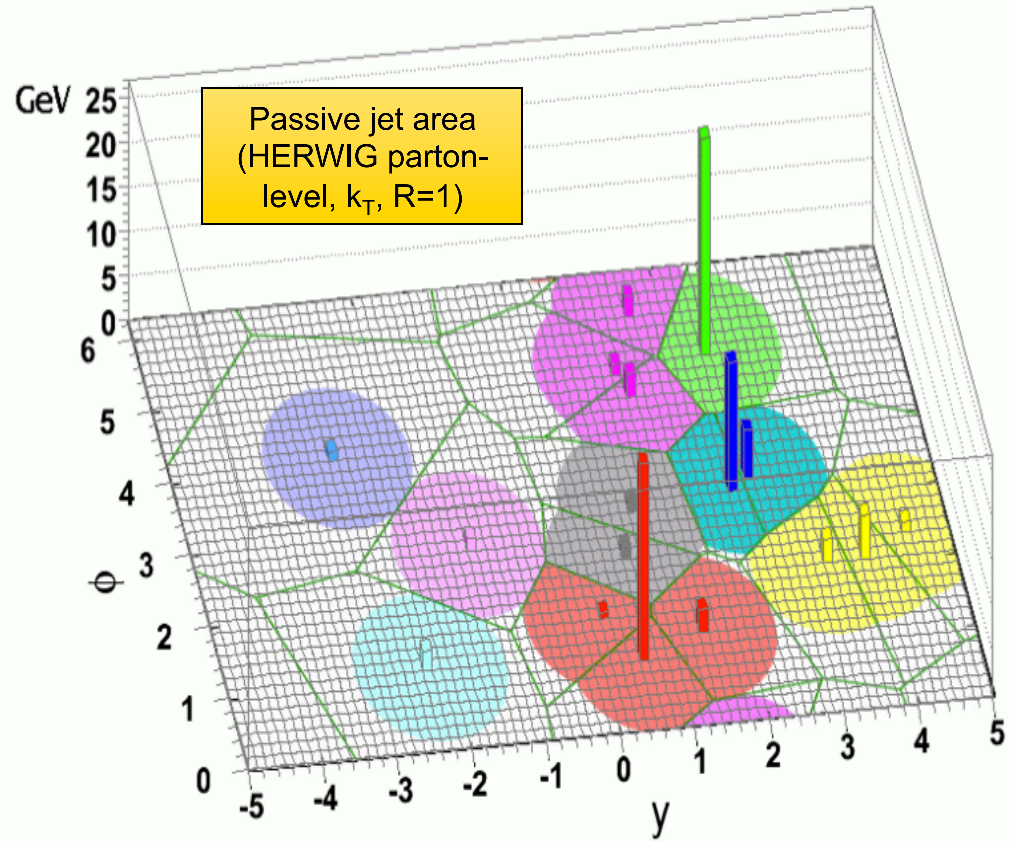
Cacciari et al. 2008

Jet catchment area: A handle for subtracting the effects of pile-up and UE.

Idea: particles from UE etc. are ~uniformly distributed → jet's susceptibility to this effect ~ proportional to (geometric) "catchment" area of the jet.

e.g. "passive" area: (geometric) area for which soft "ghost" particles are clustered into the jet

… can be calculated on jet-by-jet basis



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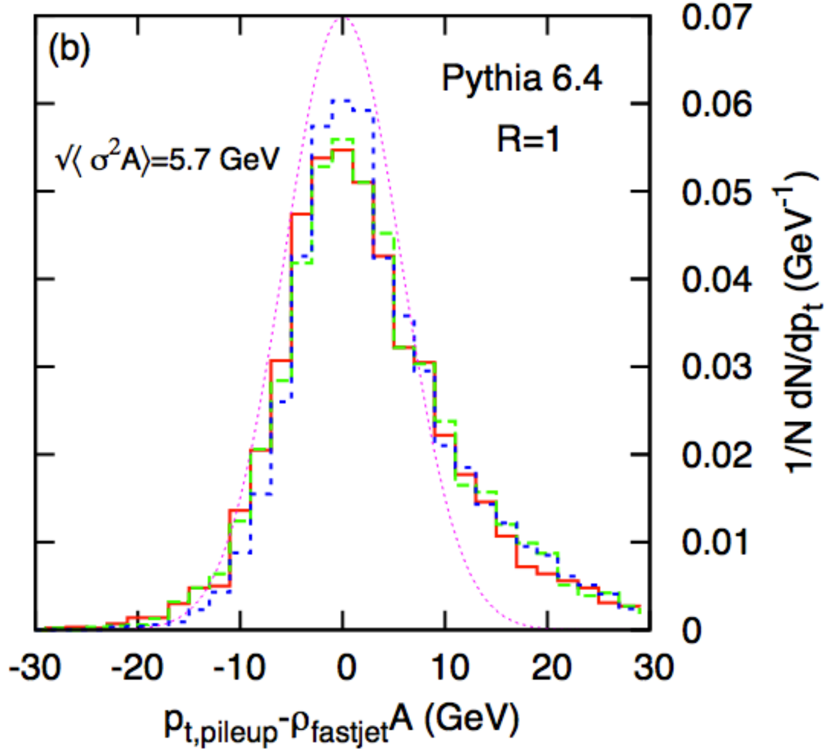


MC test - pile-up subtraction:

Difference of

– PU contribution to jet p_T (MC truth) and

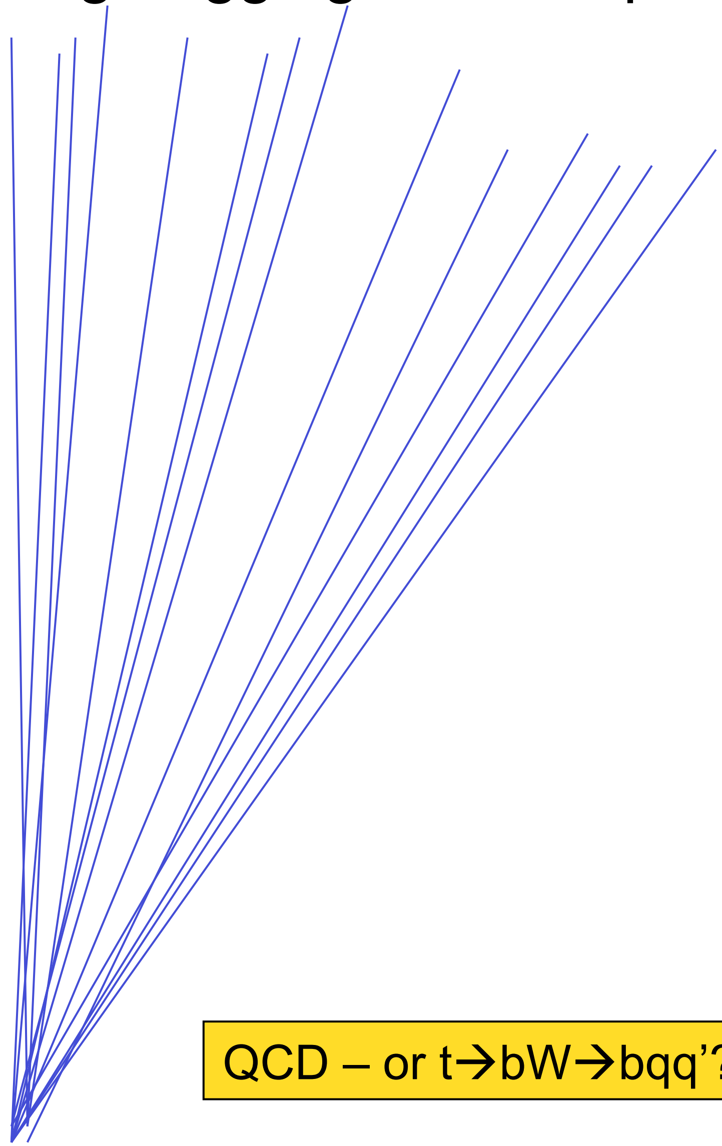
– subtraction term based on jet area A and energy density / unit area ρ

→ centered on 0 and narrow!!!

→ tool for suppressing / quantifying PU!

NEW CONCEPTS FOR JETS 2

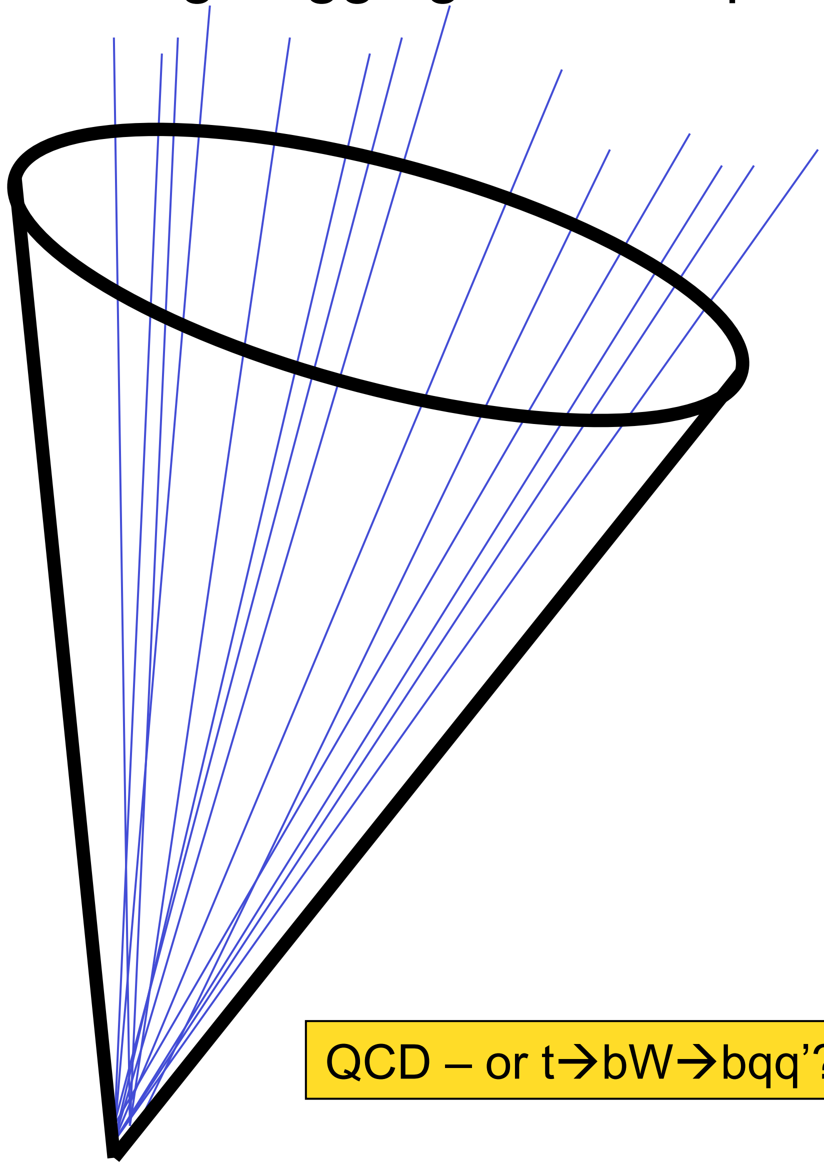
Trimming, pruning, filtering, tagging boosted particles …



QCD – or t→bW→bqq'?

NEW CONCEPTS FOR JETS 2

Trimming, pruning, filtering, tagging boosted particles …



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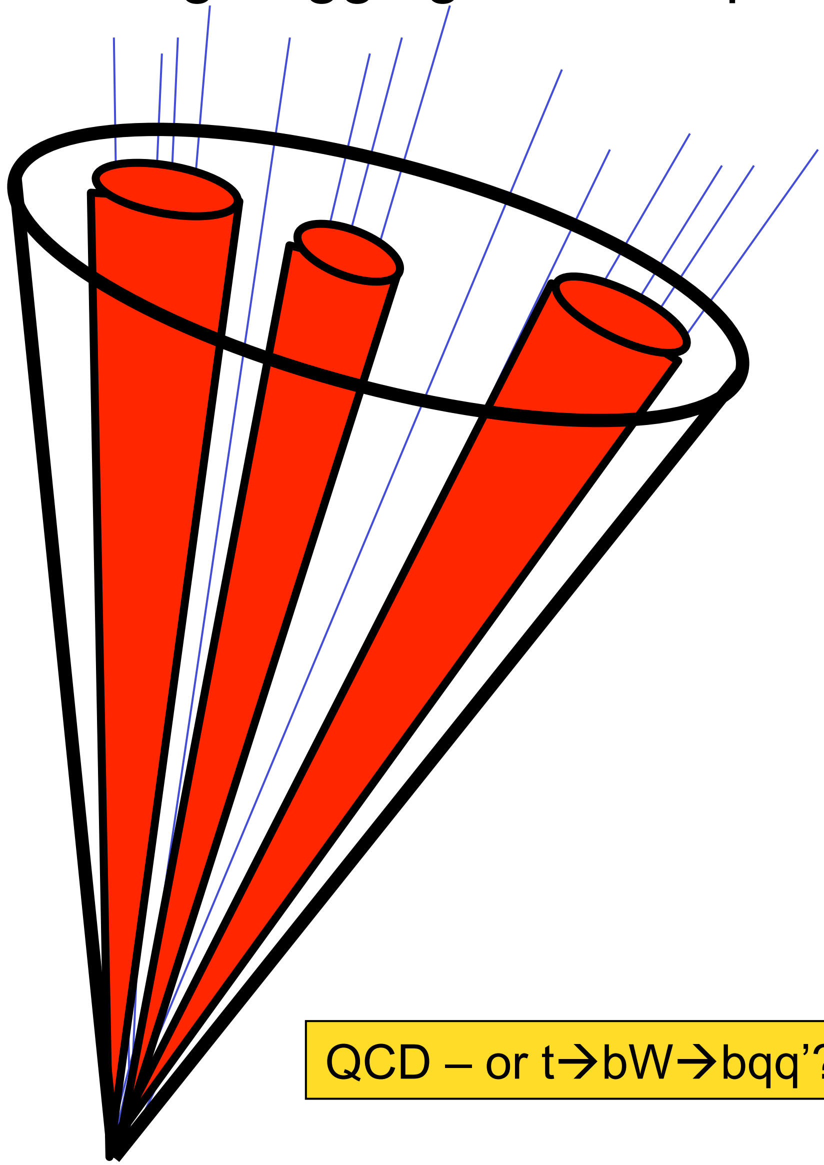

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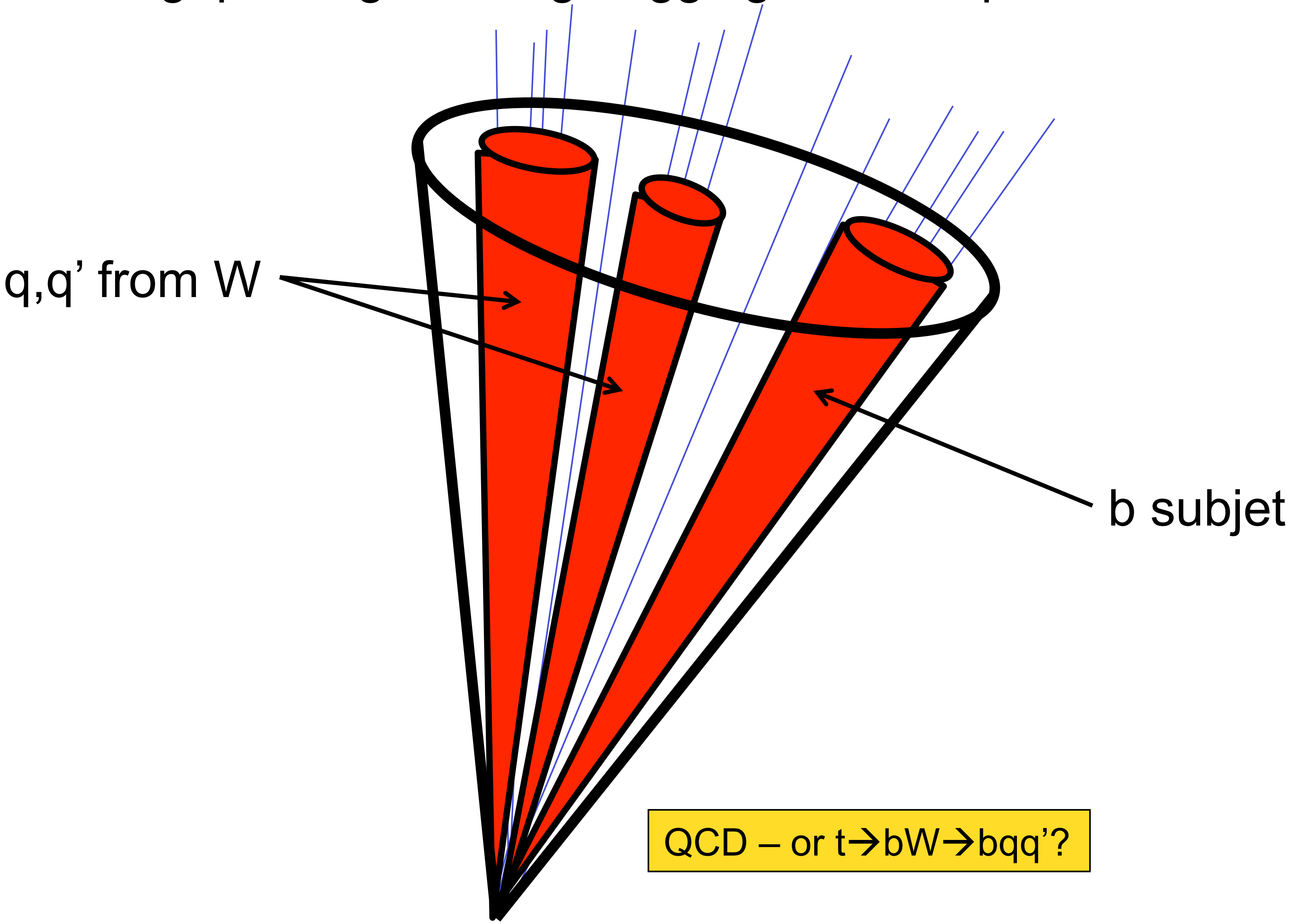


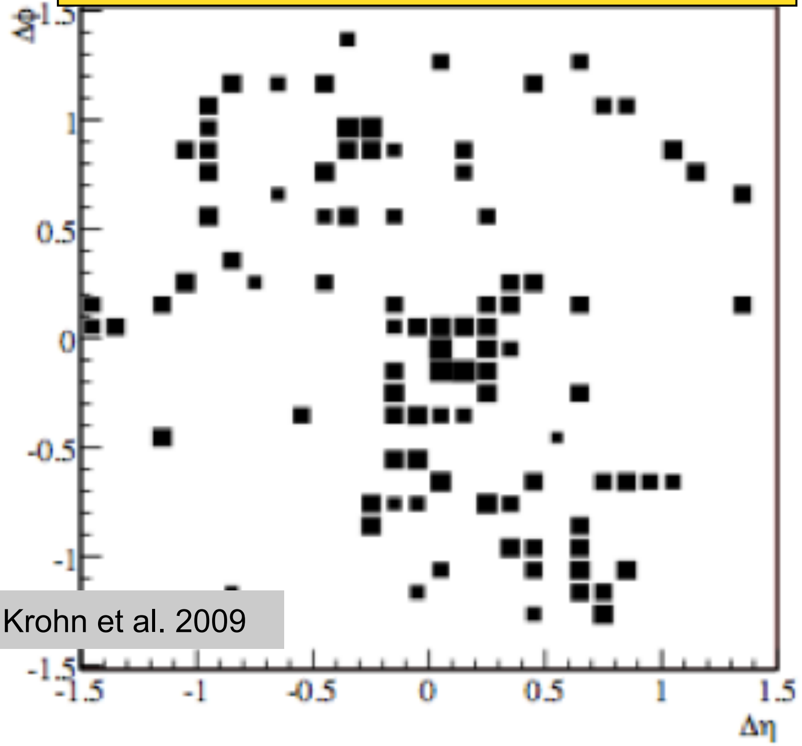
NEW CONCEPTS FOR JETS 2

Trimming, pruning, filtering, tagging boosted particles …

Idea: Assist identification of heavy decays by improving resolution and reducing soft effects.

- e.g. by only using only N hardest subjets (assign correct decay products, correct mass)

QCD jet or boosted t→bW→bqq'
(all decay products close by)?



Krohn et al. 2009

Remove particles or pseudo-jets from splittings without significant creation of invariant mass …

… and look at the remainder …

NEW CONCEPTS FOR JETS 2

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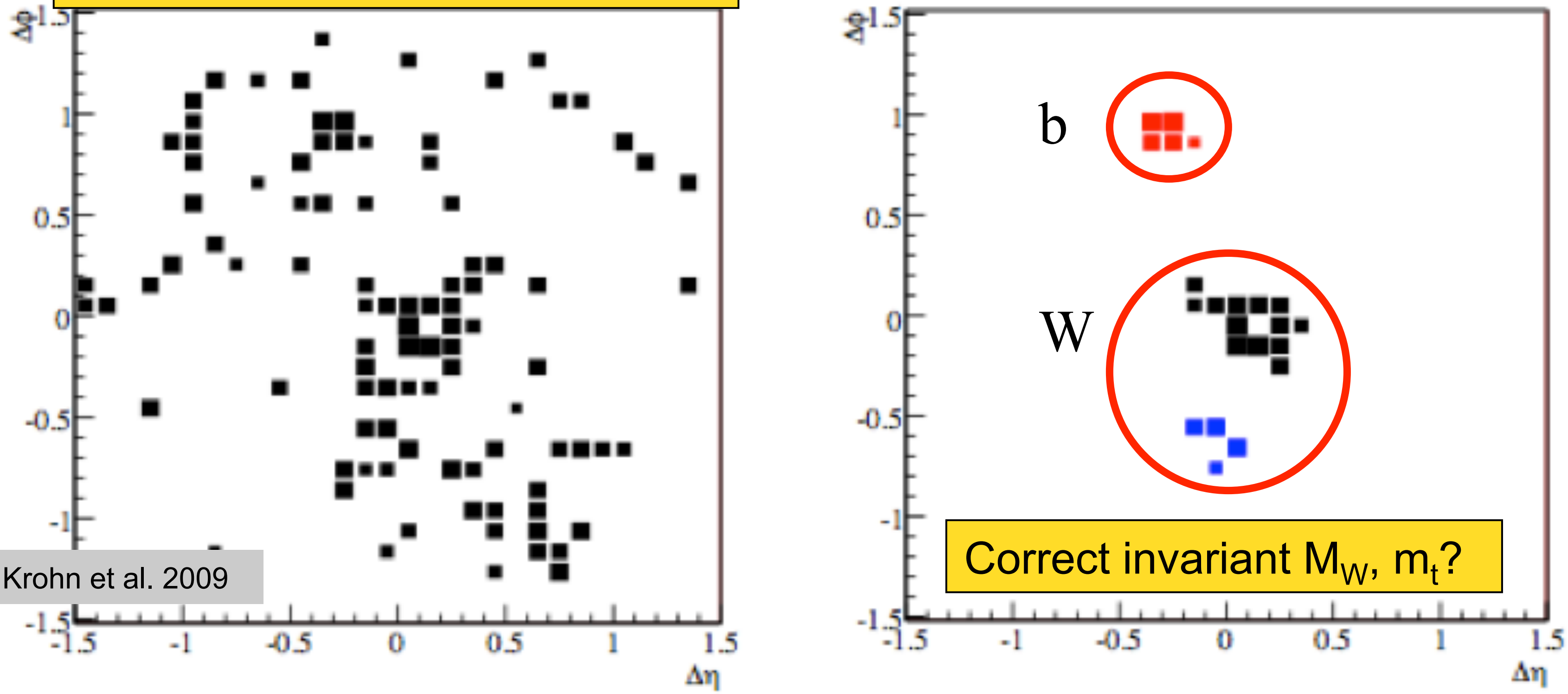


Krohn et al. 2009

Correct invariant M_W, m_t?

NEW CONCEPTS FOR JETS 2

Trimming, pruning, filtering, tagging boosted particles …

Idea: Assist identification of heavy decays by improving resolution and reducing soft effects.

Other approach: "Pruning"

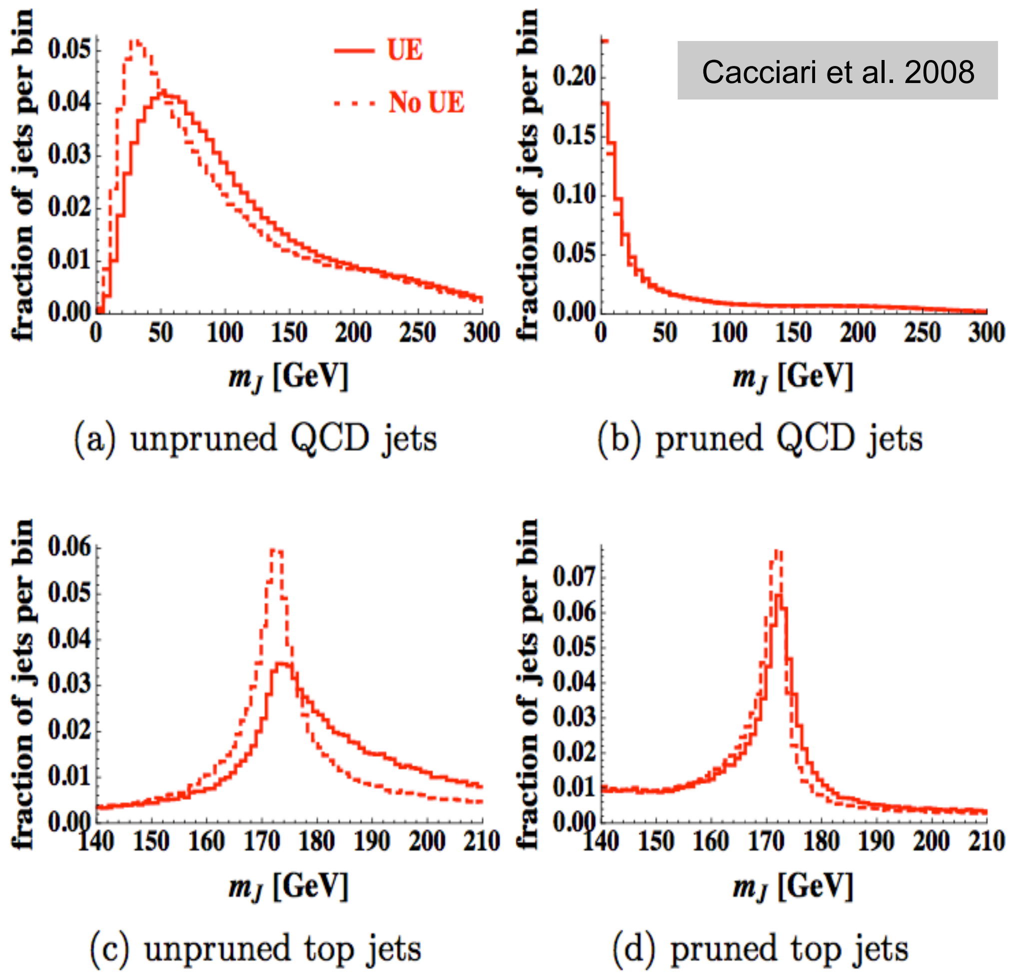
Discard soft, large-angle radiation – unlikely to come from heavy particle decays!

Again boosted top decays:

➔ Reduced QCD jet mass, reduced QCD background!

➔ Improved top jet resolution and mass peak position!

➔ Reduced influence of underlying event!



SUMMARY

Jets – an important tool at the energy frontier

¶ History and concepts – algorithms and theory

¶ Jet measurements at HERA, Tevatron, …

¶ What have we learned?
- Strong coupling
- PDFs
- …

¶ Jets at the LHC – tests of QCD

¶ Jets and new physics …

¶ … and new concepts like trimming, pruning, jet areas etc.

¶ … and apologies for many omissions, and thanks to all the people who, over the years, taught me a lot about jets, QCD and physics.

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