Jet Physics with CMS

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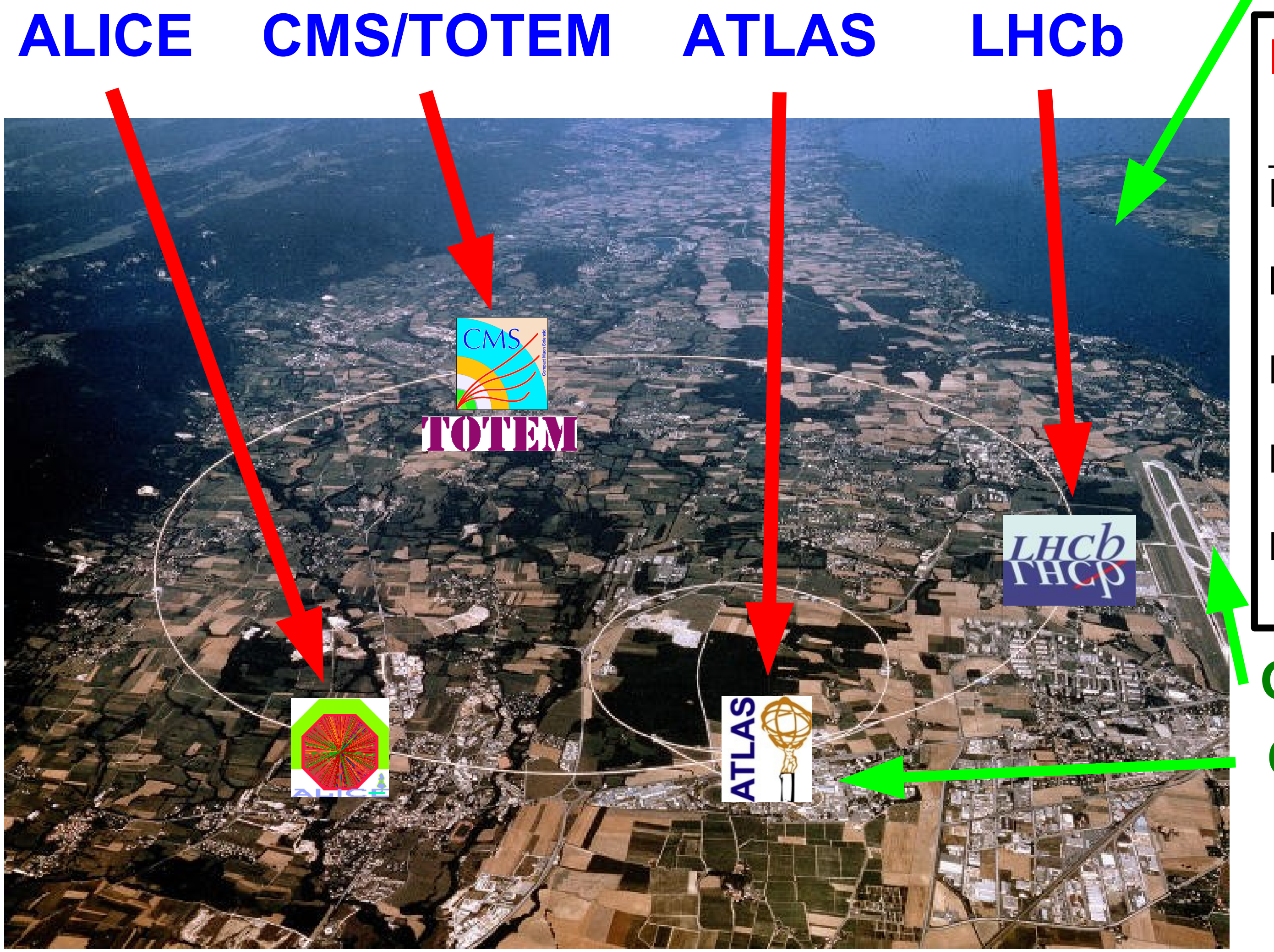
Outline

- LHC Start-up
- The CMS Detector
- Jet Algorithms
- Expected Jet Performance in CMS
- Jets in QCD Analyses ...
- ... and beyond

The Large Hadron Collider

Four interaction points with the experiments:



ALICE **CMS/TOTEM** **ATLAS** **LHCb**

Lake Geneva

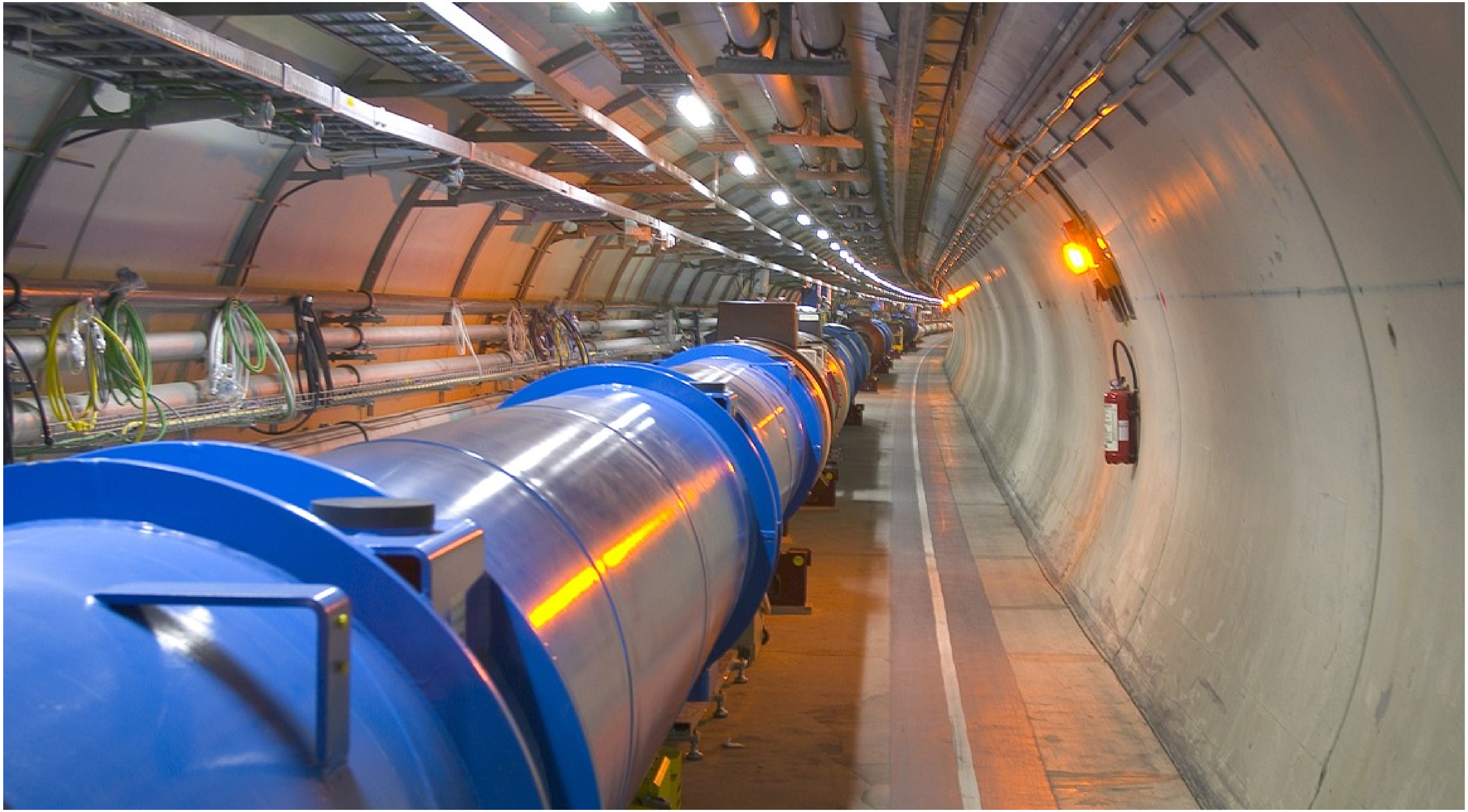
Geneva Airport

CERN Meyrin Site

LHC Design Parameters:

	pp	AA
Energy/Nucleon/TeV:	7.0	2.76
Bunch separation/ns:	25	100
Design Luminosity/$cm^{-2}s^{-1}$:	10^{34}	10^{27}
Number of bunches:	2808	592
No. of particles/bunch:	$1.15 \cdot 10^{11}$	$7.0 \cdot 10^{7}$

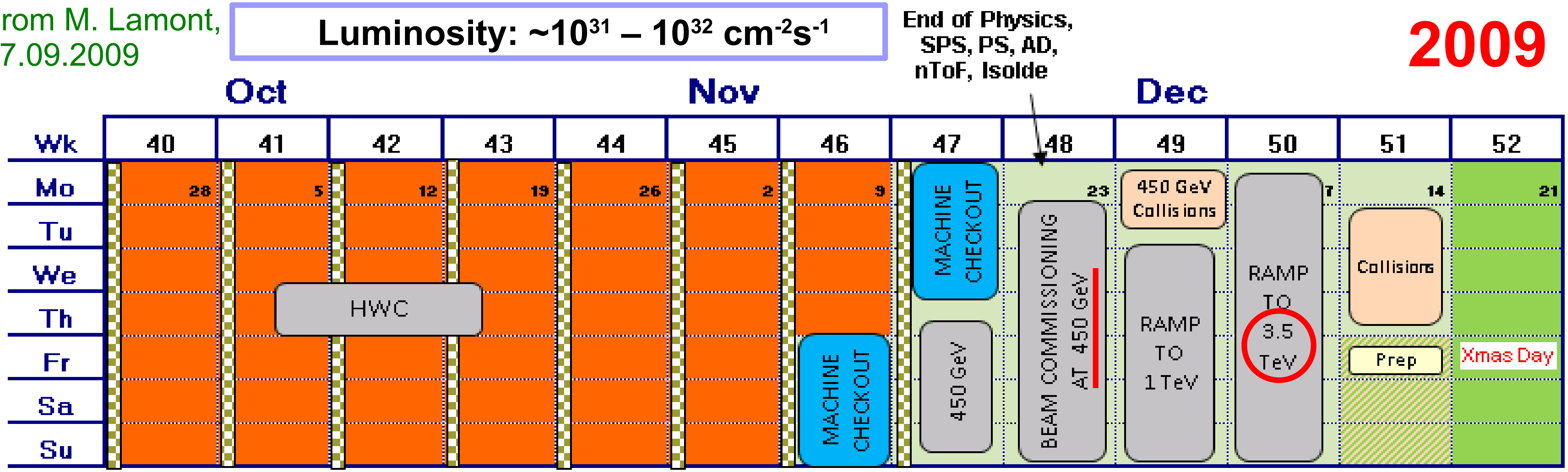
The Tunnel View



LHC Start-Up

From M. Lamont, 07.09.2009

Luminosity: ~10^{31} – 10^{32} cm^{-2}s^{-1}



🟩 Technical Stop

🟩 Beam commissioning

▨ SPS et al physics

- All dates approximate…
- Reasonable machine availability assumed
- Stop LHC with beam ~19th December 2009, restart ~ 4th January 2010

- 2009: - 1 month commissioning

- 2010: - 1 month pilot & commissioning

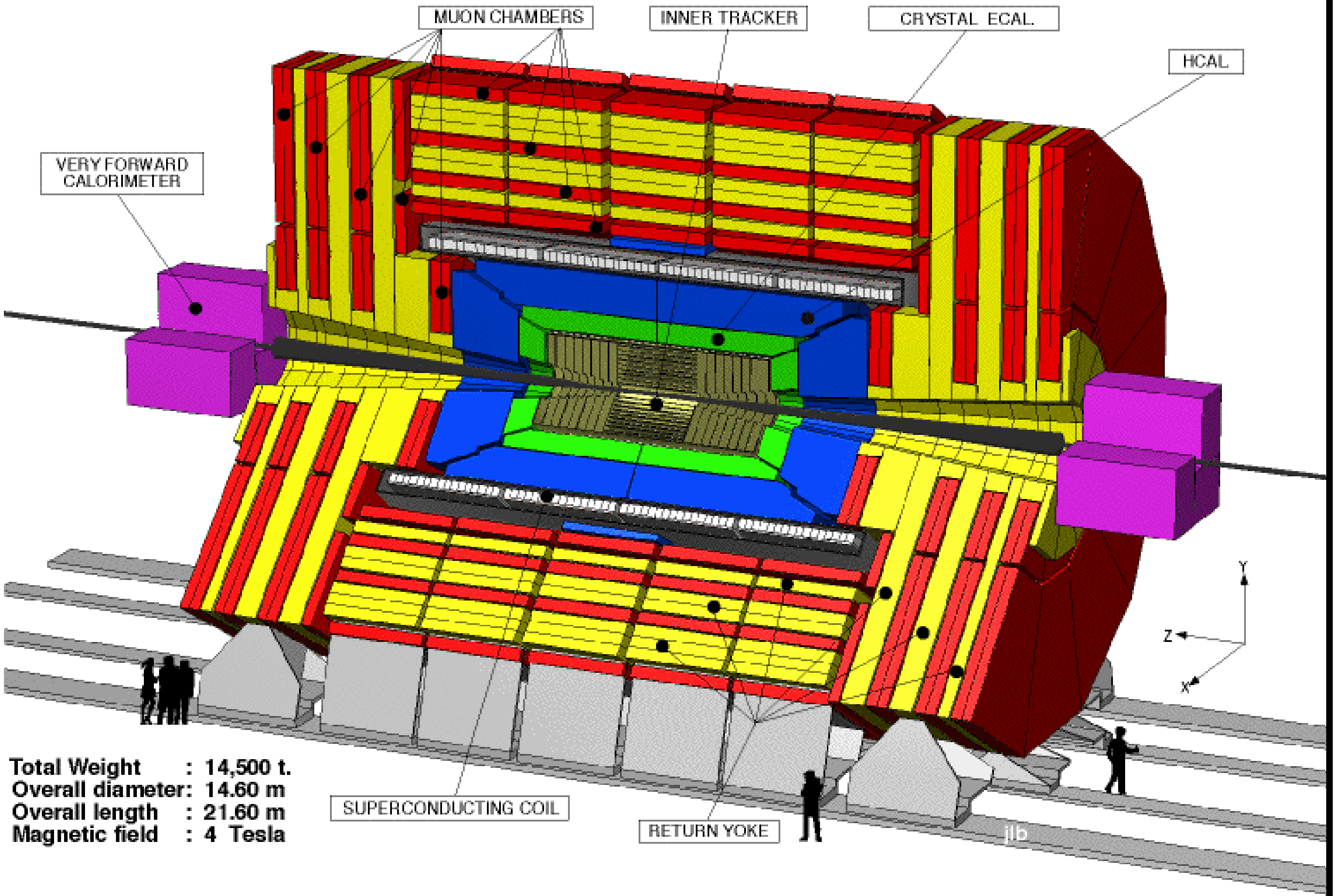
- 3 month 3.5 TeV

- 1 month step-up

- 5 month 4 - 5 TeV

- 1 month ions

The CMS Detector



General purpose pp collider experiment:

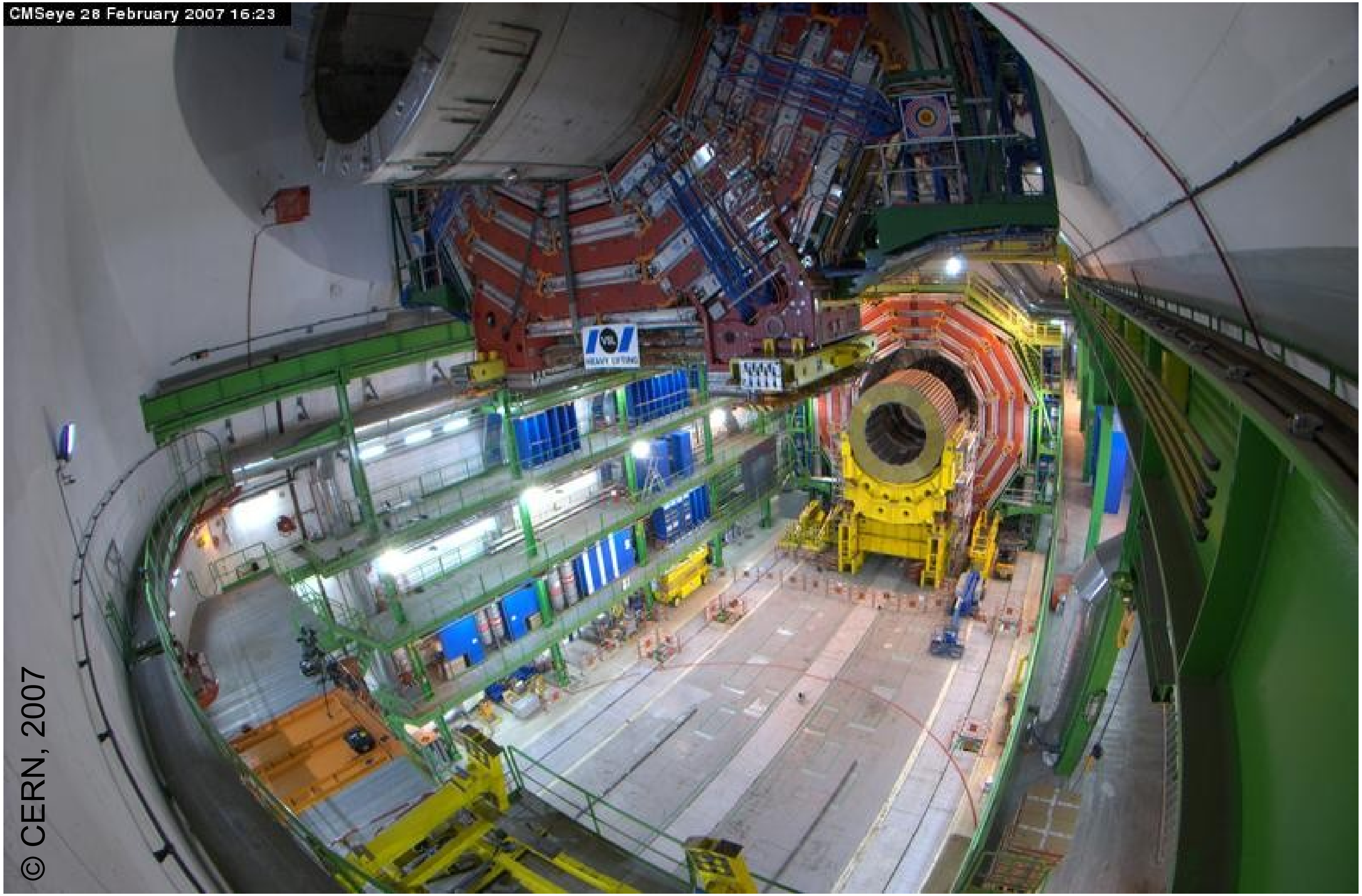
Searches for Higgs bosons, other new particles (SUSY,..) and new phenomena; Precision measurement of SM parameters like top and W masses, ...; Heavy ion program.

Plus TOTEM:

Total cross section, elastic pp scattering, diffractive dissociation.

For details see e.g.:
"The CMS Experiment at the CERN LHC", JINST 2008, 0803, S08004.

The Cavern View



© CERN, 2007

28.02.2007
Lowering of largest detector piece YB0

Weight:
1920 t

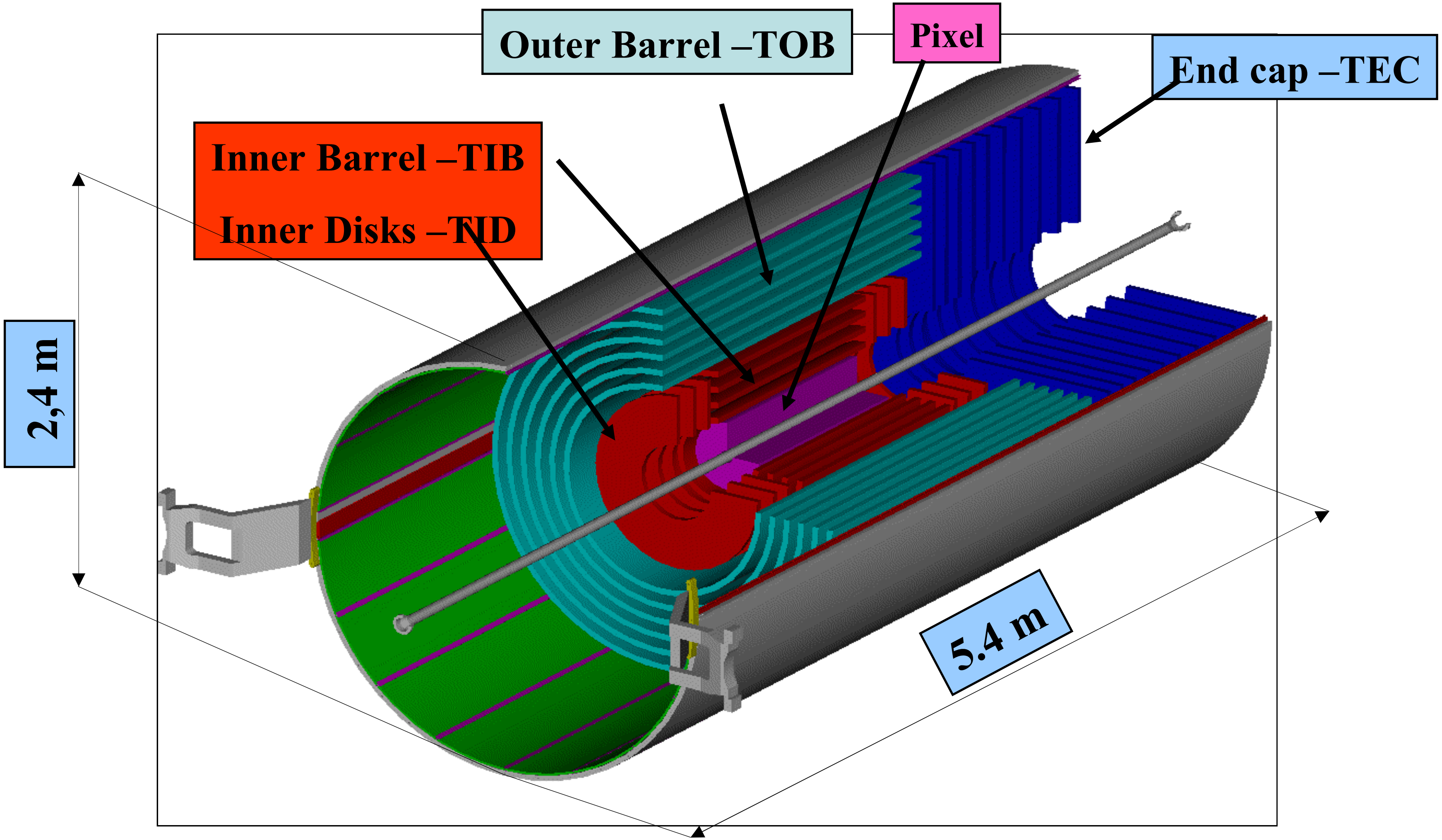
Size:
16x17x13m^3

Descent:
100 m

Margin:
20 cm

Duration:
10 h

Silicon Tracker



Pixel:
1 m^2 area
66 M pixels

Strips:
200 m^2 area
10 M strips

Momentum resolution (μ, 100 GeV):
1 – 2% (up to |η| ≈ 1.6)

Reconstruction efficiency:
μ: ≈99%, π: ≈90% (up to |η| ≈ 1.6)

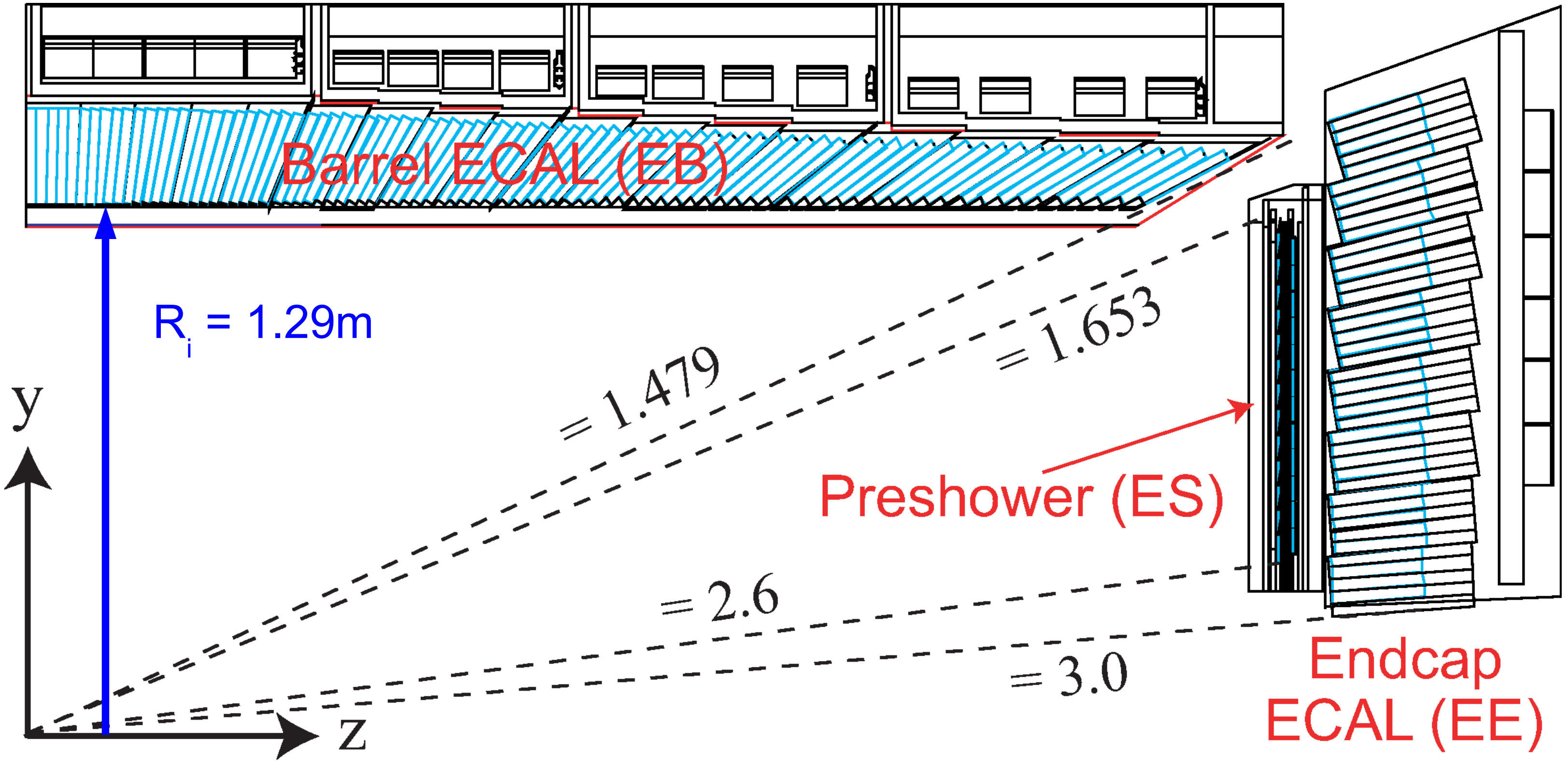
Electromagnetic Calorimeter

<u>Barrel (EB)</u>:
- η segments: 2x85
- φ segments: 360

→ 61200 crystals ($PbWO_4$, 26 X_0)

→ Δη x Δφ ≈ 0.0174 x 0.0174

Segmentation



Energy resolution from test beam:
S = 2.8%, N = 120 MeV, C = 0.30%

$$\left(\frac{\sigma}{E}\right)^2 = \left(\frac{S}{\sqrt{E}}\right)^2 + \left(\frac{N}{E}\right)^2 + C^2$$

Segmentation

<u>Endcaps (EE)</u>:
- (x,y) grid on two halfs
- front face 28 x 28 mm^2

→ 2 x 2 x 3662 crystals = 14648 ($PbWO_4$, 25 X_0)

Hadronic Calorimeter

<u>HCAL (tower structure)</u>:
- Barrel (HB): |η| < 1.4, 2592 towers
- Endcaps (HE): 1.3 < |η| < 3.0, 2592 "
- Outside coil (HO): |η| < 1.26, 2160 "

→ Depth (Brass abs. & plast. scint., ≈ 6 - 10 λ_N)

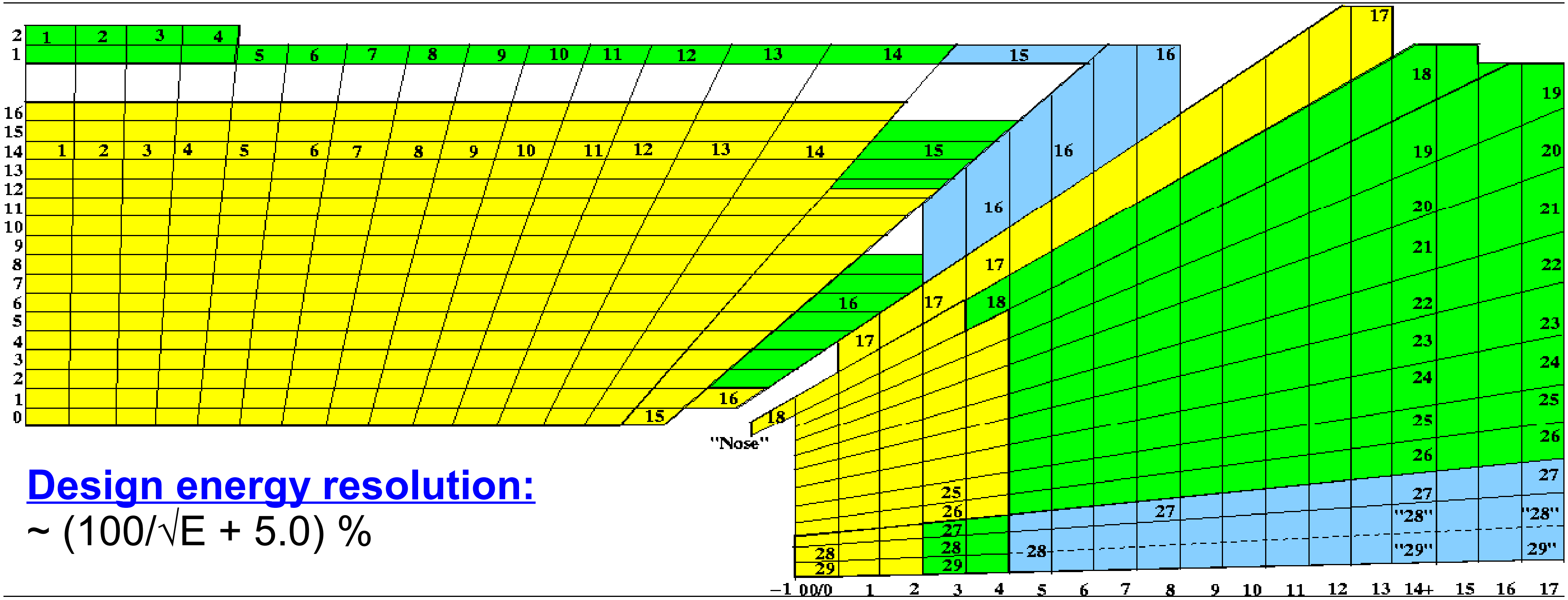
→ Δη x Δφ ≈ 0.087 x 0.087 → 0.350 x 0.175

- Forward (HF): 2.9 < |η| < 5.0 (not shown)

→ 2 x 864 towers (Brass,quartz fibers, ≈ 10 λ_N)

→ Δη x Δφ ≈ 0.111 x 0.175 → 0.302 x 0.350

<u>CASTOR calorimeter</u> (not shown):
- 5.1 < |η| < 6.5, ≈ 22 X_0, ≈ 10 λ_N



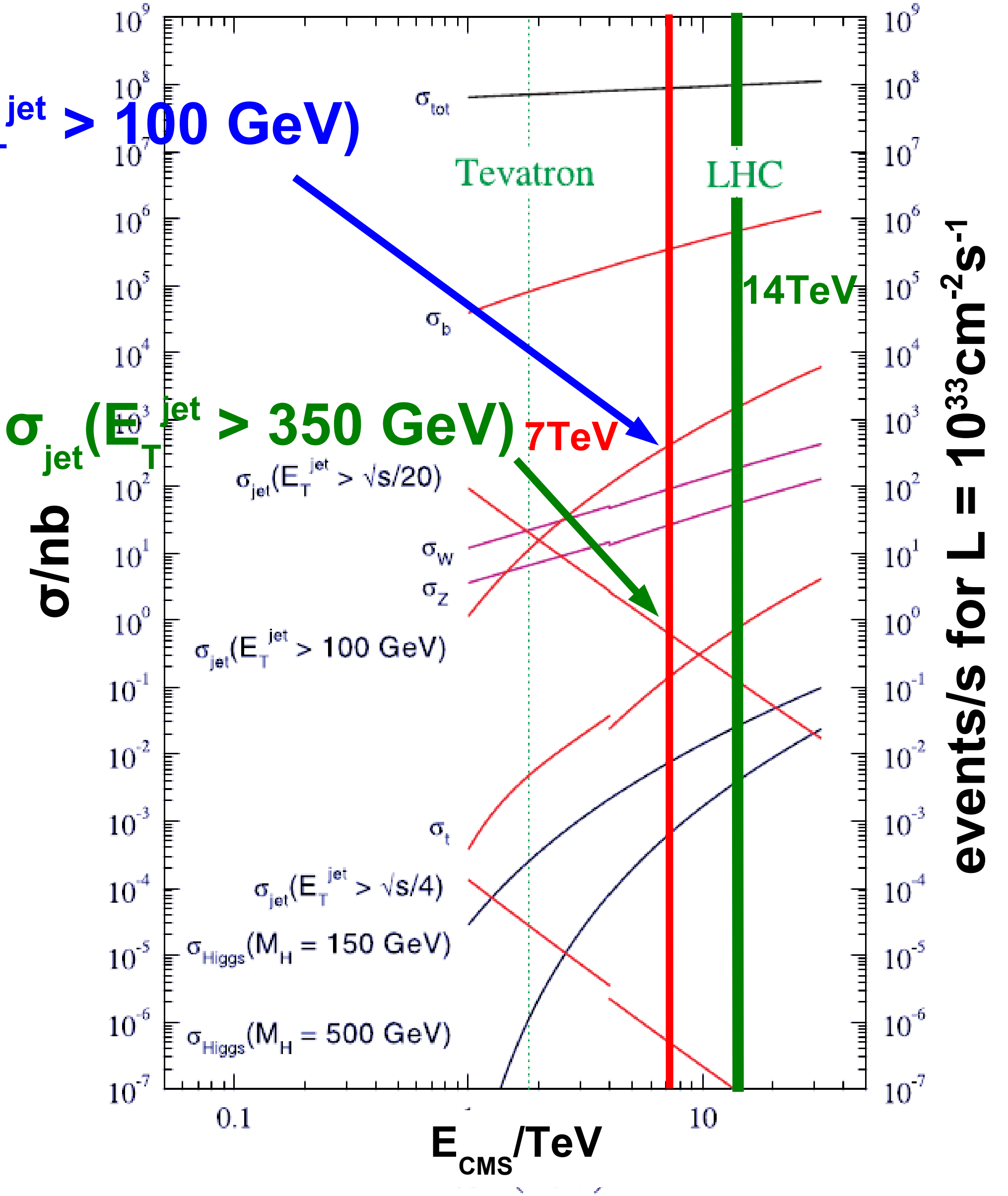
<u>**Design energy resolution:**</u>

~ (100/√E + 5.0) %

QCD Jets at the LHC Start-up

Still enough events/sec left ☺

- Startup with QCD:
  - Not much statistically limited
  - First measurements at multi TeV energy scale
  - Re-establishment of Standard Model, i.e. test extrapolations from Tevatron energies
  - Background to be understood for almost everything
  - Physics commissioning of CMS
  - Be prepared for surprises ...

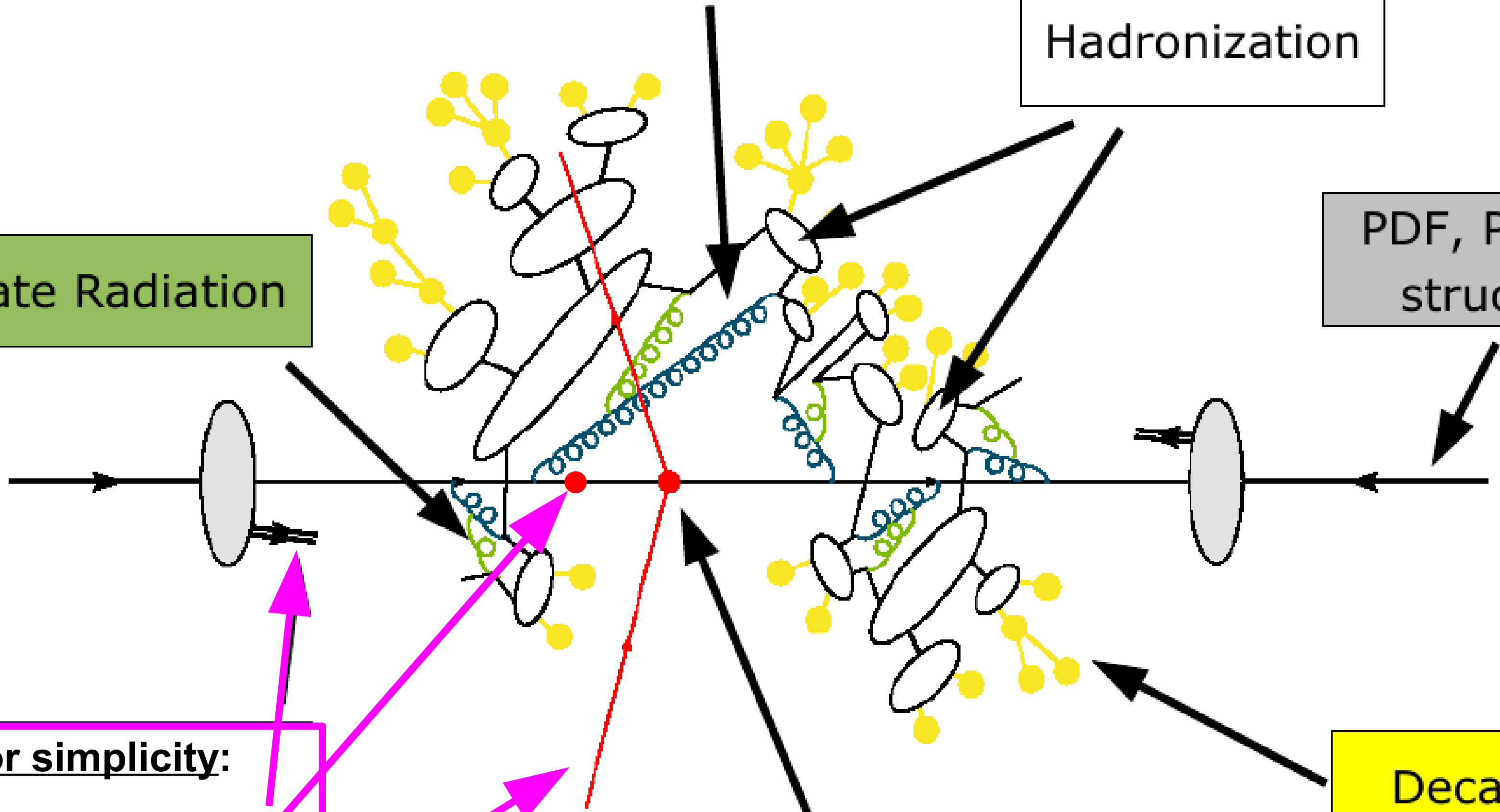


$\sigma_{jet}(E_T^{jet} > 100\ \mathrm{GeV})$

$\sigma_{jet}(E_T^{jet} > 350\ \mathrm{GeV})$

Sketch of a pp Scatter

S. Gieseke



Initial State Radiation

Hadronization

Final State Radiation

PDF, Proton structure

Decay

Hard Process (ME)

Not shown for simplicity:

Beam Remnants

Multiple Interactions

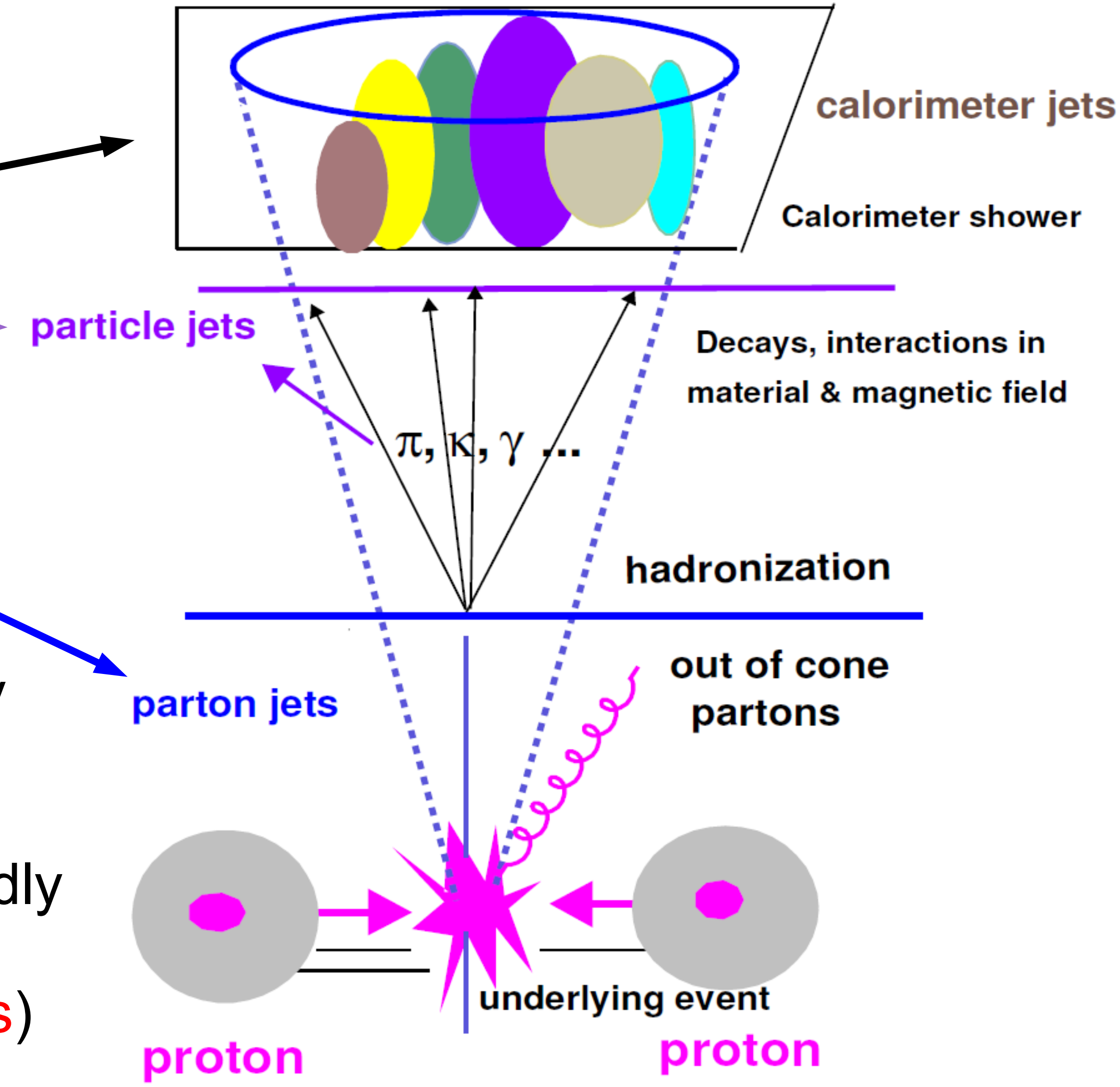
FSR off the hard partons

PLUS … a Detector!

Jet Algorithms 1/3

Primary Goal:

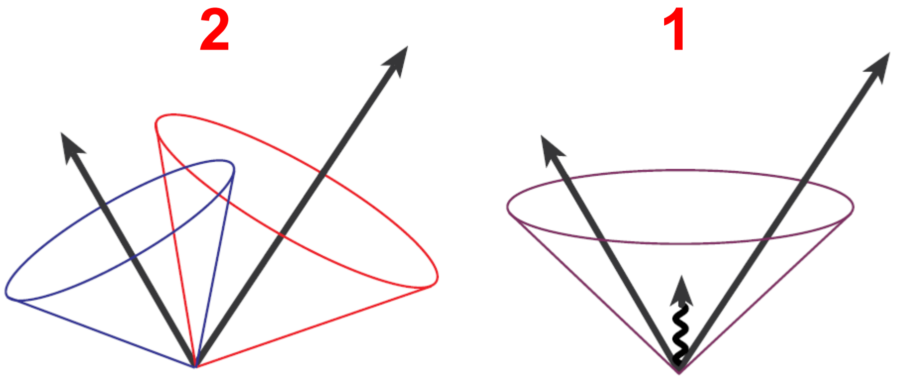
Establish a good correspondence between:
- detector measurements
- final state particles and
- hard partons



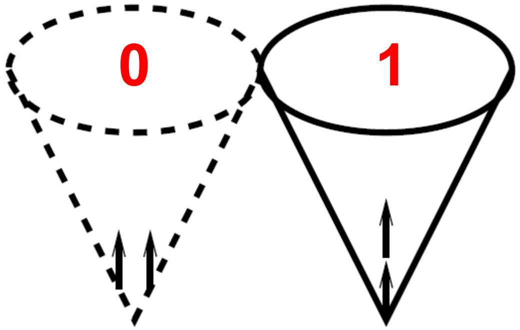
Two classes of algorithms:
- Cone algorithms: "Geometrically" assign objects to the leading energy flow objects in an event (favorite choice at hadron colliders)
- Sequential recombination: Repeatedly combine closest pairs of objects (favorite choice at e^+e^- & ep colliders)

Jet Algorithms 2/3

- **Jet Algorithm Desiderata (Theory):**
  - **Infrared safety**
  - **Collinear safety**
  - **Longitudinal boost invariance**
    (recombination scheme!)
  - **Boundary stability**
    (→ 4-vector addition, rapidity y)
  - **Order independence**
    (parton, particle, detector)
  - **Ease of implementation**
    (standardized public code?)



IR unsafe: Sensitive to the addition of soft particles



Coll. unsafe: Sensitive to the splitting of a 4-vector (seeds!)

"Snowmass Accord", FNAL-C-90-249-E
Tevatron Run II Jet Physics, hep-ex/0005012

Jet Algorithms 3/3

- **Jet Algorithm Desiderata (Experiment):**
  - **Computational efficiency and predictability**
    (use in trigger?, reconstruction times?)
  - **Maximal reconstruction efficiency**
  - **Minimal resolution smearing and angular biasing**
  - **Insensitivity to pile-up**
    (mult. collisions at high luminosity ...)
  - **Ease of calibration**
  - **Detector independence**
  - **Fully specified**
    (details?, code?)
  - **Ease of implementation**
    (standardized public code?)

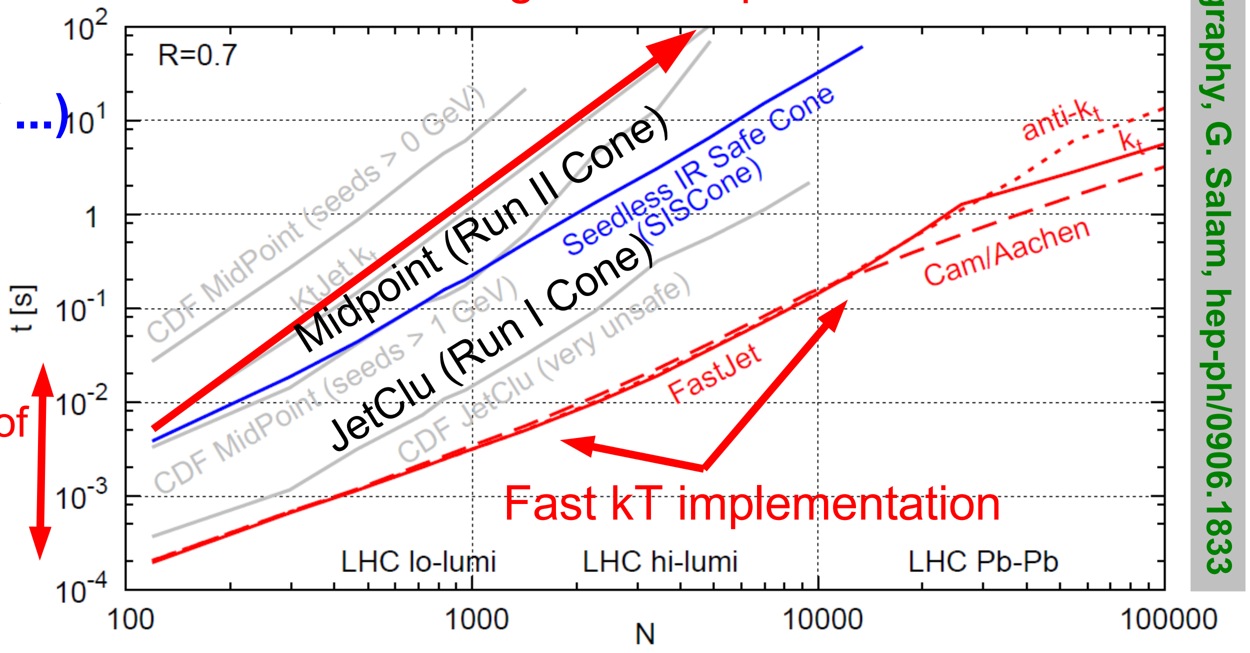
$$d_{ij} = \min(k_{ti}^{2p}, k_{tj}^{2p}) \frac{\Delta_{ij}^2}{R^2}$$

$$d_{iB} = k_{ti}^{2p} ,$$

$$\Delta_{ij}^2 = (y_i - y_j)^2 + (\phi_i - \phi_j)^2$$

p = 1: kT
p = 0: Cambridge/Aachen
p = -1: anti-kT

Original kT implementation



2-3 orders of magnitude

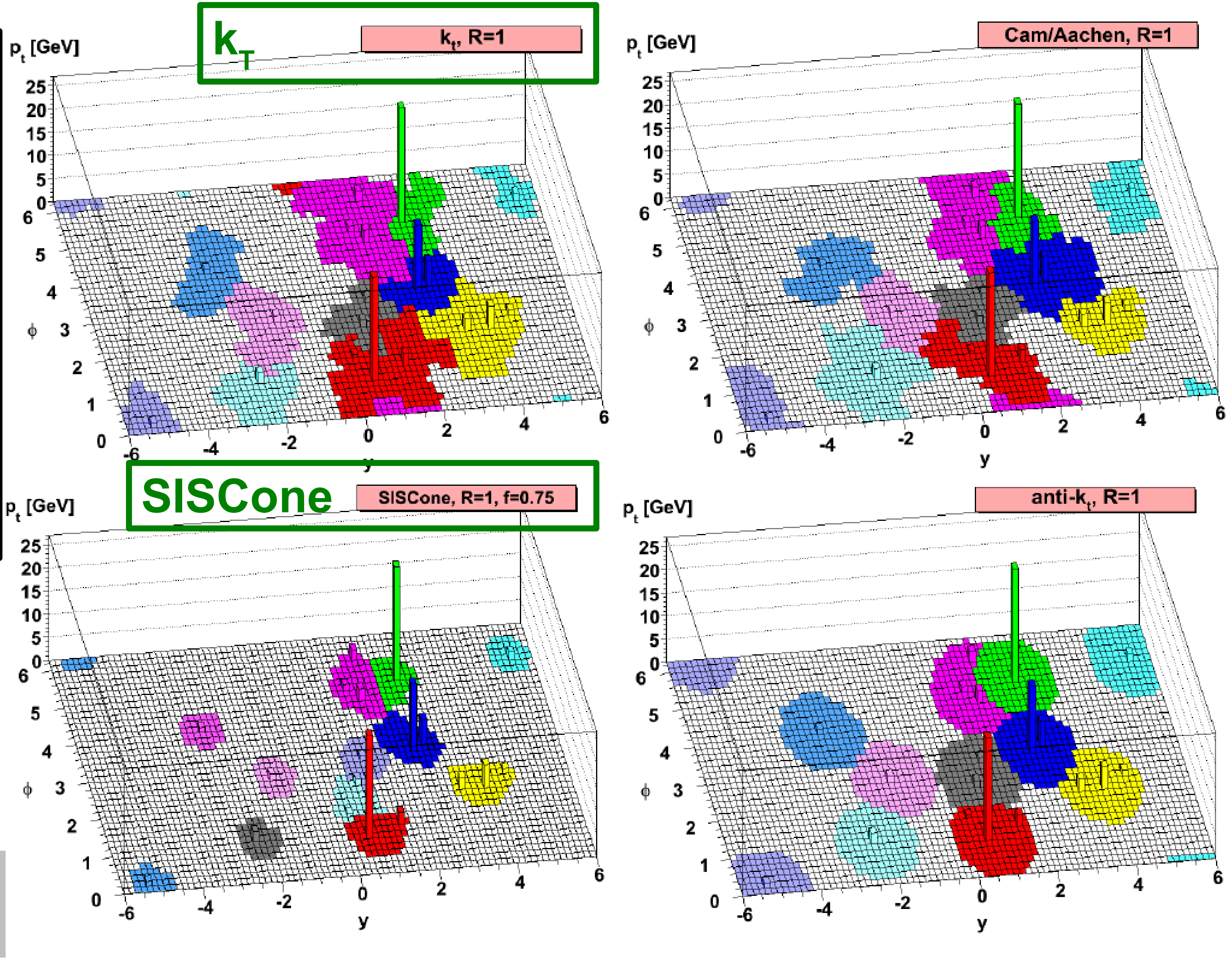
Fast kT implementation

Jetography, G. Salam, hep-ph/0906.1833

Jet Algorithms in CMS

Current standards of CMS:

- Iterative Cone: R = 0.5
  (IR unsafe, used in trigger)
- SISCone: R = 0.5, 0.7
- k_T: R = 0.4, 0.6
  (SISCone & k_T advised for analyses, but habits die hard)
- Cam/Aachen only used in jet substructure for now
- Anti-k_T actively discussed
  (recently adopted by ATLAS)

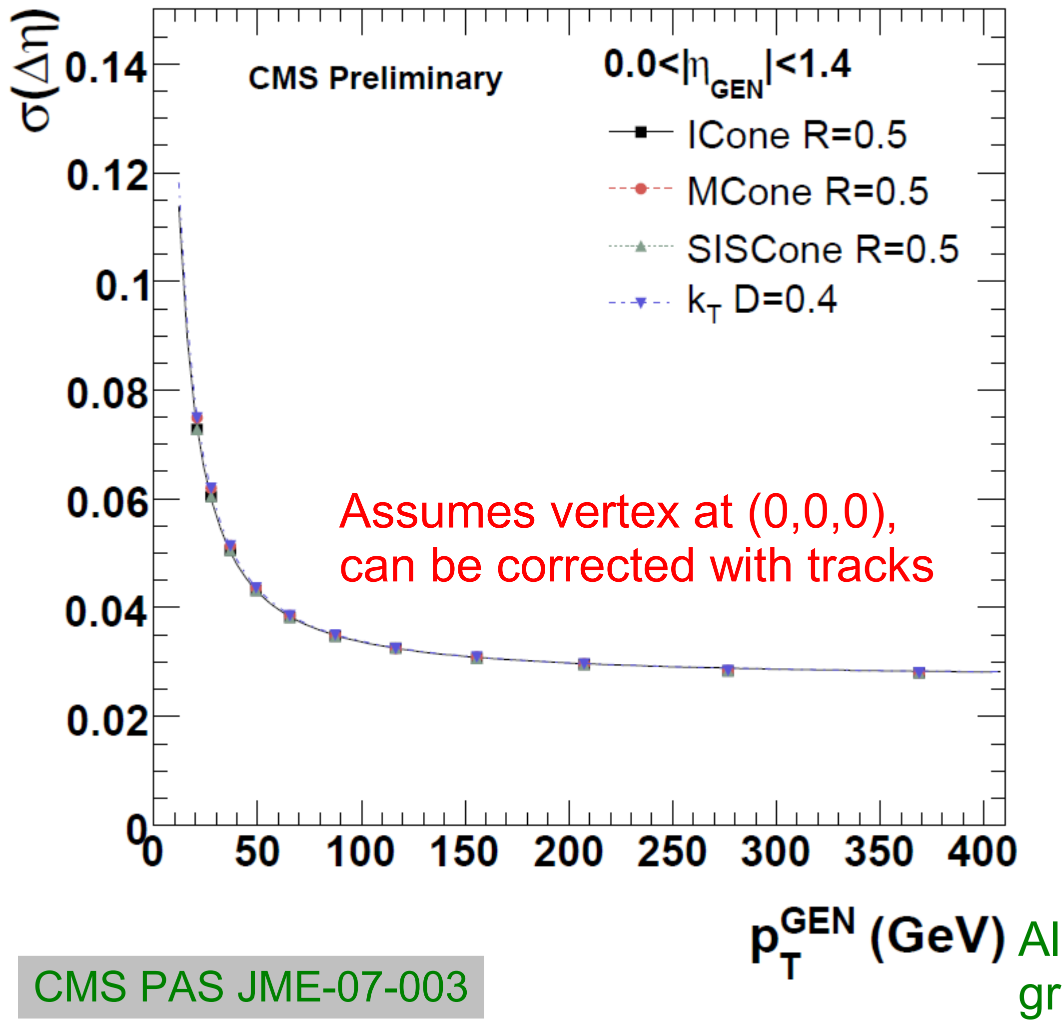


Fast kT, Cacciari/Salam, PLB641, 2006
SISCone, Salam/Soyez, JHEP05, 2007
anti-kT, Cacciari et al., JHEP04, 2008

Jet Angular Resolutions

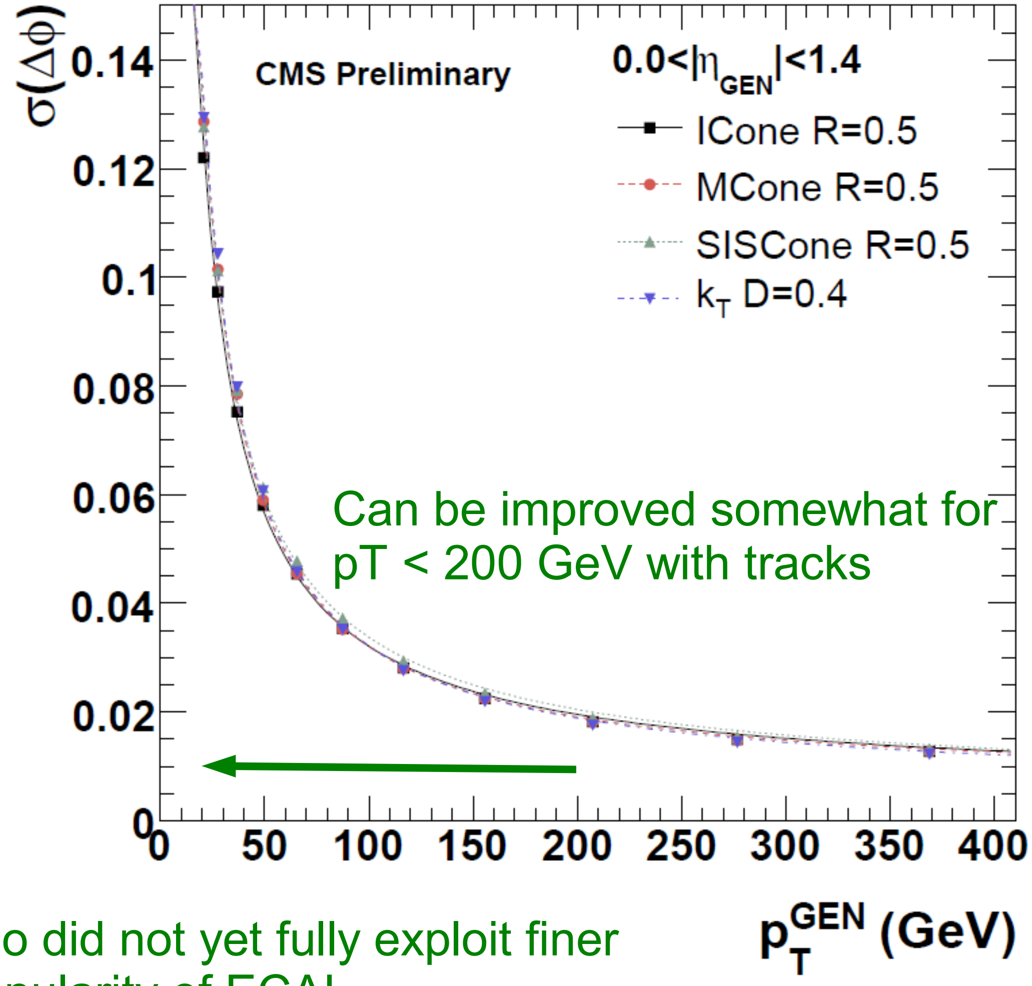
CMS detector simulation, calorimeter towers, E_{CMS} = 14 TeV

Resolution in jet rapidity



Assumes vertex at (0,0,0), can be corrected with tracks

Resolution in jet azimuth



Can be improved somewhat for pT < 200 GeV with tracks

Also did not yet fully exploit finer granularity of ECAL

CMS PAS JME-07-003

Jet Energy Resolution

CMS detector simulation, calorimeter towers, E_{CMS} = 10 TeV

Jet energy resolution (JER):

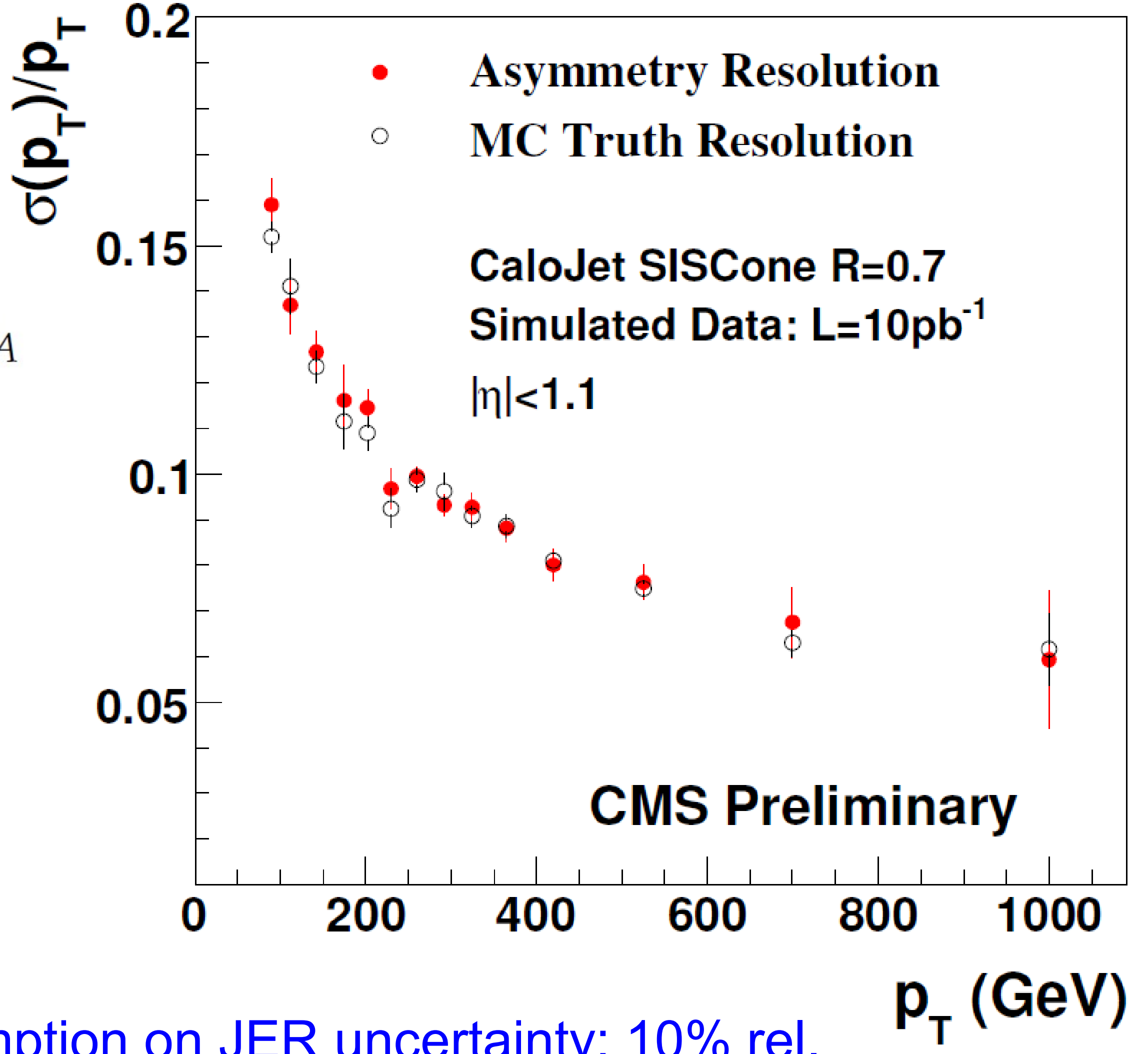
- Can be measured from data using Asymmetry Method used:
  For dijet events:

$$A = \frac{(p_T^{jet1} - p_T^{jet2})}{(p_T^{jet1} + p_T^{jet2})} \Rightarrow \left(\frac{\sigma_{p_T}}{p_T}\right) = \sqrt{2}\sigma_A$$

  Used at Tevatron.
- Comparison using MC information (matched jets) gives consistent results

Jet reconstruction efficiency:

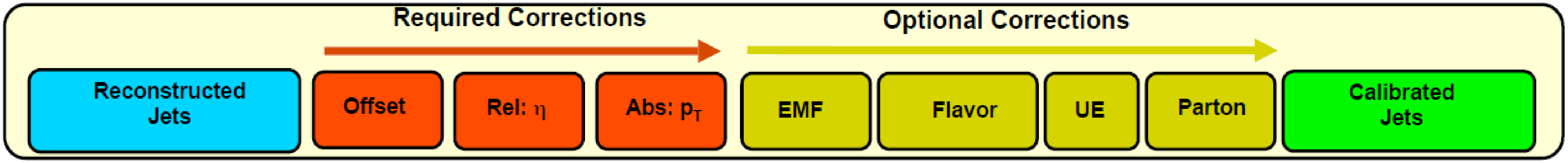
- From tag-and-probe with Z+1jet events, > 95% for pT_Z >≈ 25 GeV
  ≈ 100% for pT > 30 GeV



CMS PAS JME-09-007

Initial assumption on JER uncertainty: 10% rel.

Jet Energy Calibration



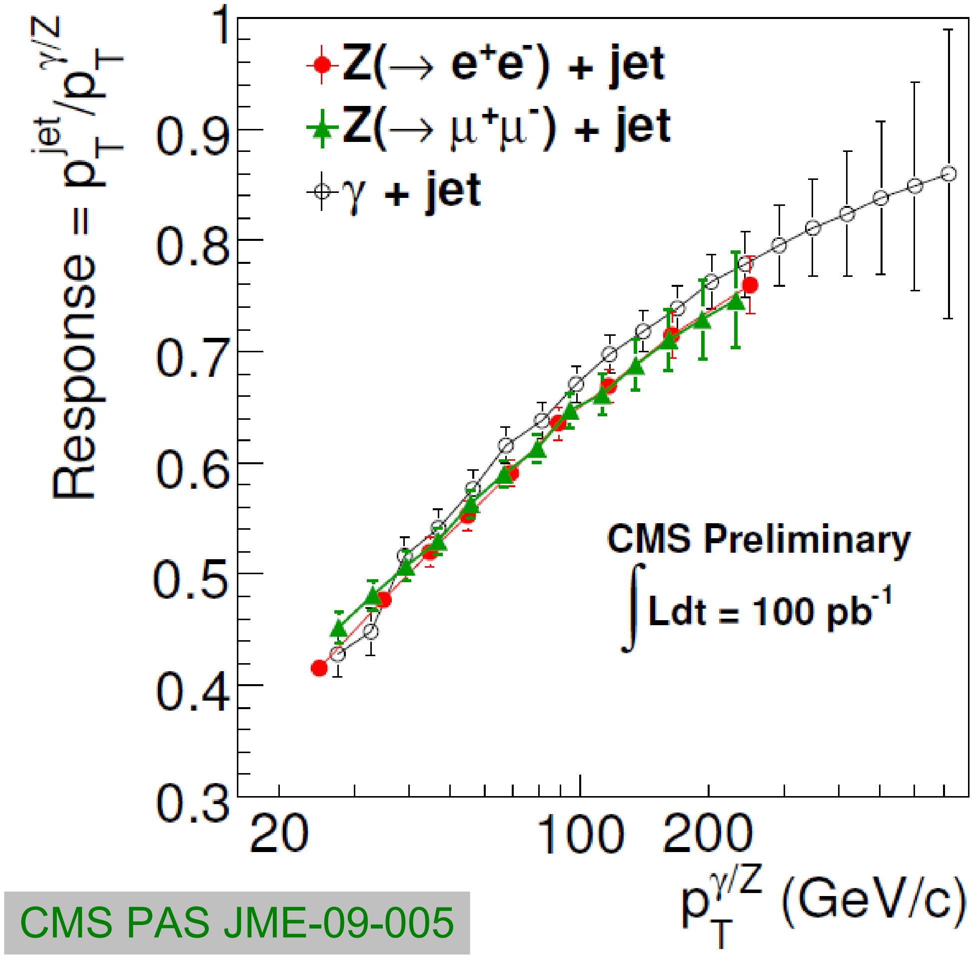
- **Offset:** Correct for detector noise and pile-up (use random triggers = zero bias, special read-out for noise)
- **Relative (η):** Equalize jet response in η w.r.t. control region (barrel) (dijet balancing; or MC)
- **Absolute (p_T):** Correct measured jet p_T to particle jet p_T (photon + 1jet, Z + 1jet events)
- **Optional analysis dependent corrections:** Electromagnetic fraction, flavour, … will not discuss here
- Initial assumption on JEC uncertainty: 10%

CMS PAS JME-07-002

Absolute Correction

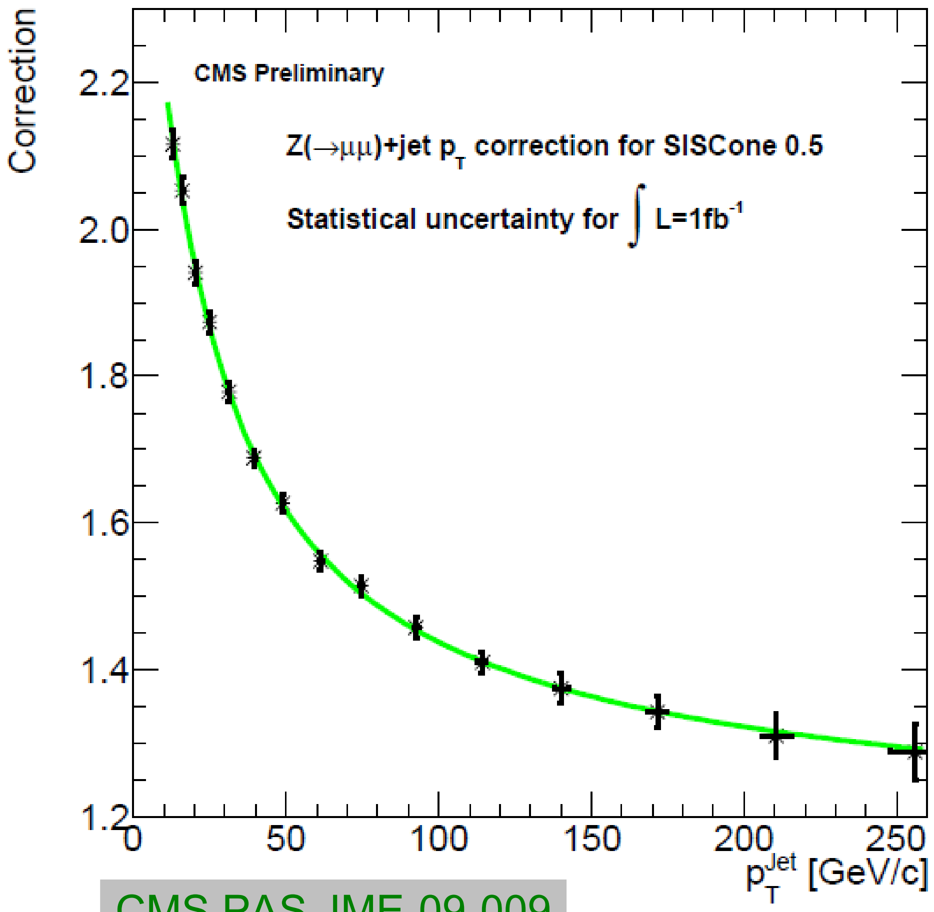
CMS detector simulation, calorimeter towers, E_{CMS} = 10 TeV

Comparison of jet responses



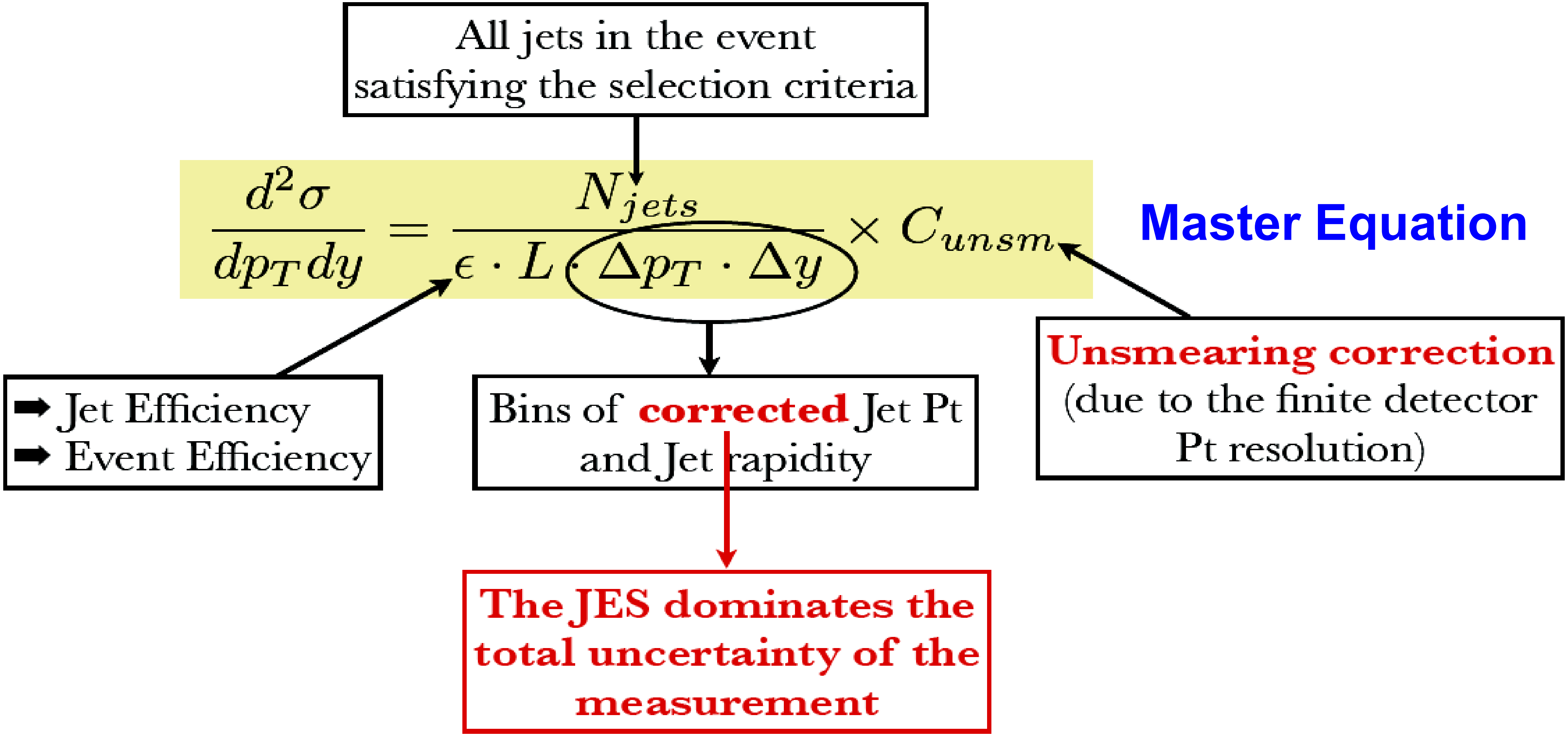
CMS PAS JME-09-005

Derived correction at the example of Z(→μμ) + 1jet



CMS PAS JME-09-009

Jet Measurements



All jets in the event satisfying the selection criteria

$$\frac{d^2\sigma}{dp_T\,dy} = \frac{N_{jets}}{\epsilon \cdot L \cdot \Delta p_T \cdot \Delta y} \times C_{unsm}$$

Master Equation

- ➡ Jet Efficiency
- ➡ Event Efficiency

Bins of **corrected** Jet Pt and Jet rapidity

Unsmearing correction (due to the finite detector Pt resolution)

The JES dominates the total uncertainty of the measurement

K. Kousouris

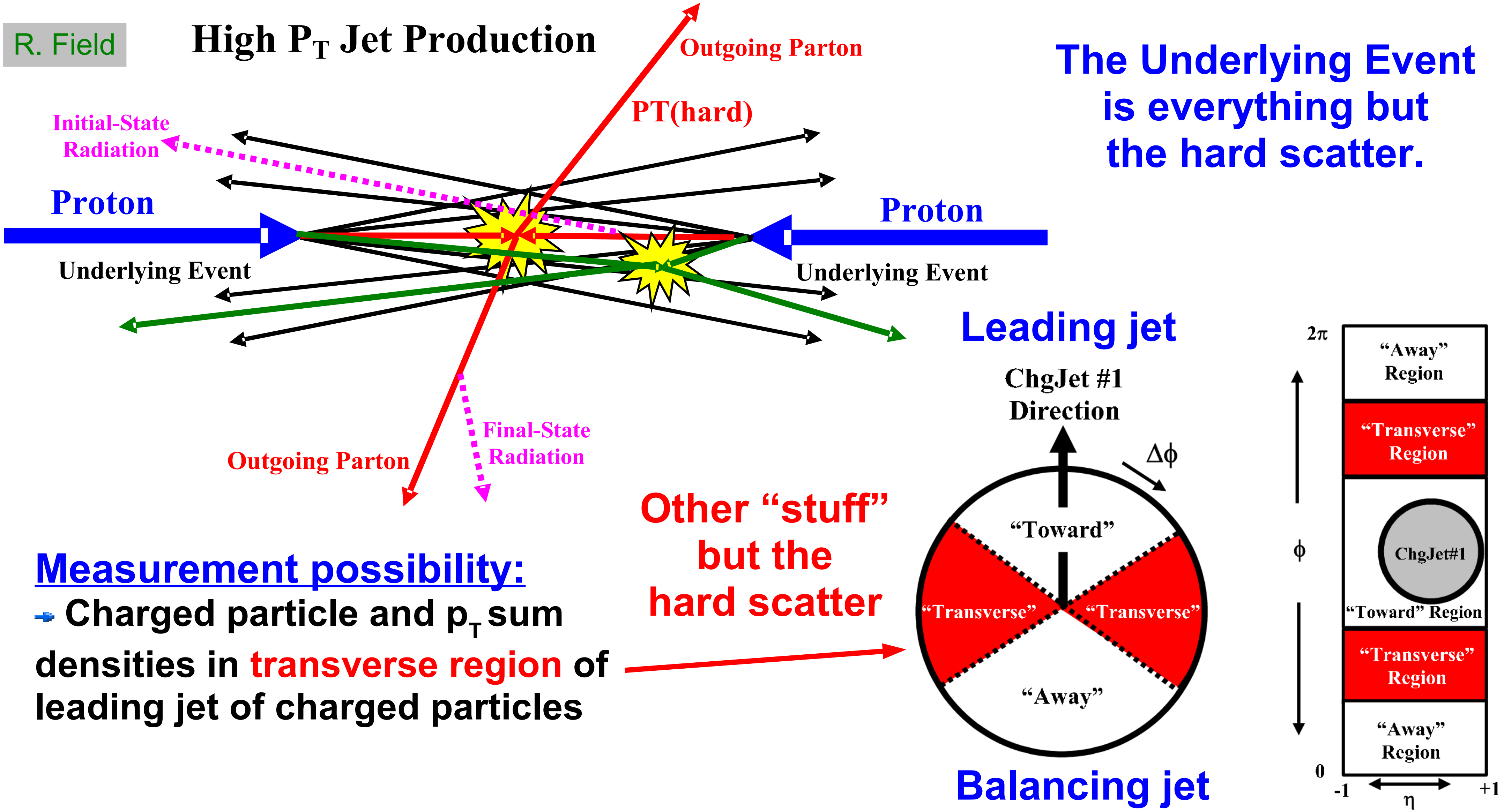
Jet Analysis Uncertainties

- Theoretical Uncertainties (~ in order of importance):
  - PDF Uncertainty
  - pQCD (Scale) Uncertainty
  - Non-perturbative Corrections
  - PDF Parameterization
  - Electroweak Corrections
  - Knowledge of $\alpha_S(M_Z)$
  - • • •
- Experimental Uncertainties (~ in order of importance):
  - Jet Energy Scale (JES)
    - Noise Treatment
    - Pile-Up Treatment
  - Luminosity
  - Jet Energy Resolution (JER)
  - Trigger Efficiencies
  - Resolution in Rapidity
  - Resolution in Azimuth
  - Non-Collision Background
  - • • •

Jet Analysis Examples

- Important especially at start-up:
  - Underlying Event
- Examples for jet analyses at high transverse momenta:
  - Inclusive jet cross section & contact interaction
    - Most complicated, requires all uncertainties to be under control!
  - Dijet mass and resonances
  - Dijet mass cross section ratios in rapidity
    - Reduced sensitivity to JES, not dependent on luminosity
  - Dijet azimuthal decorrelation
    - Less sensitive to JES, not dependent on luminosity
  - Jet shapes
  - Resonance search with boosted ttbar

The Underlying Event



The Underlying Event is everything but the hard scatter.

Other "stuff" but the hard scatter

Leading jet

Balancing jet

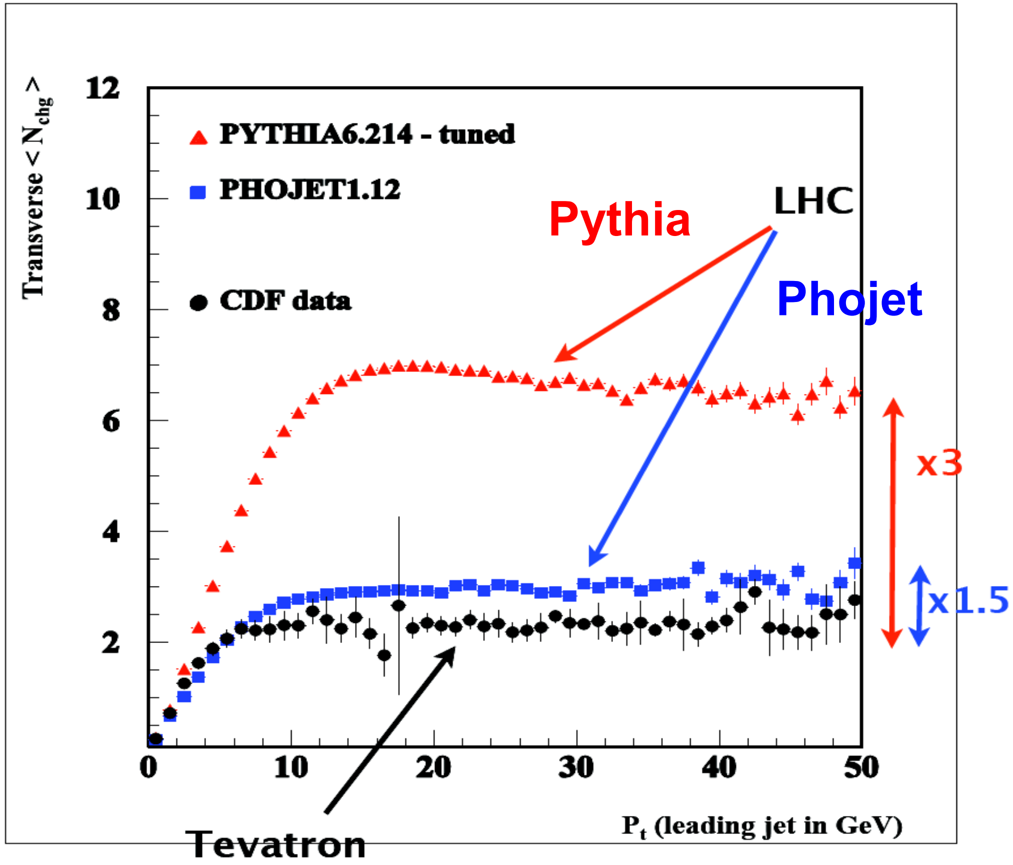
Measurement possibility:

- Charged particle and p_T sum densities in transverse region of leading jet of charged particles

The Underlying Event

Charged particle density in transverse plane vs. leading charged jet p_T

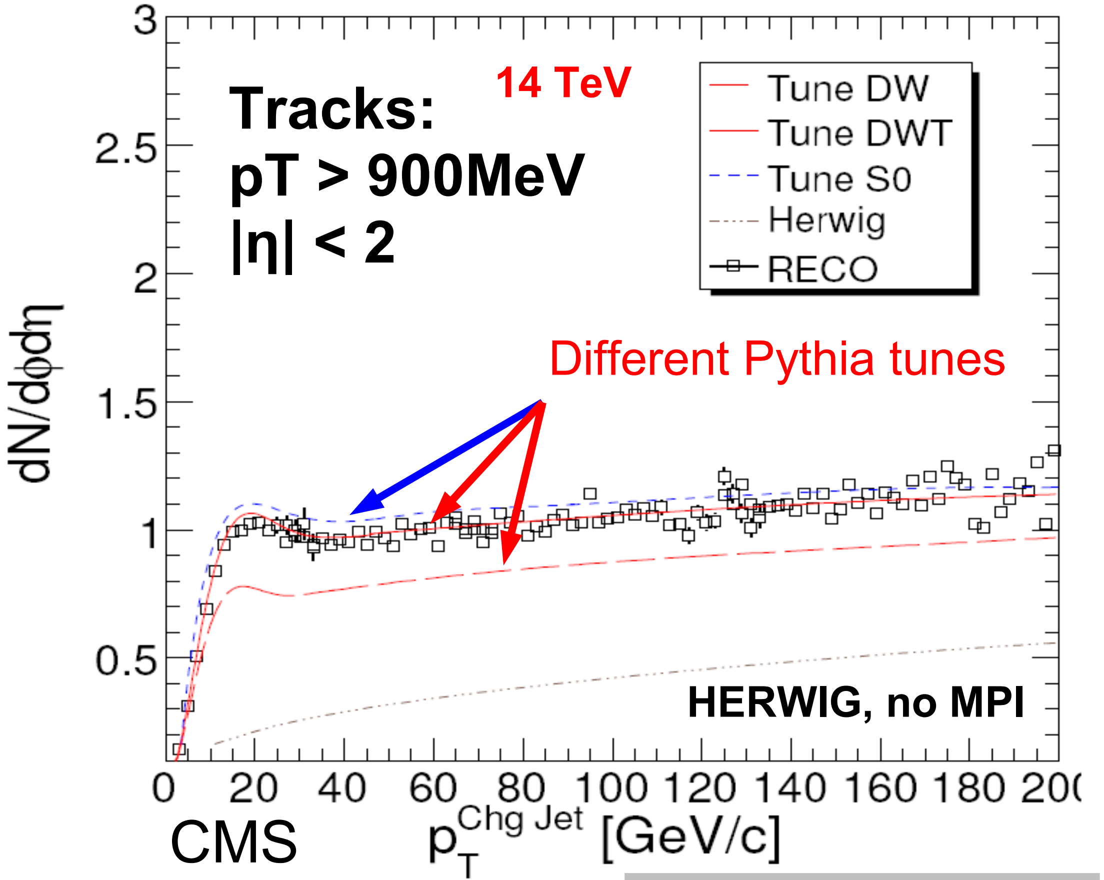
Extrapolation to LHC from CDF data



ATLAS

Comparison of different Pythia tunes

Statistics as for 100/pb



CMS PAS QCD-07-003

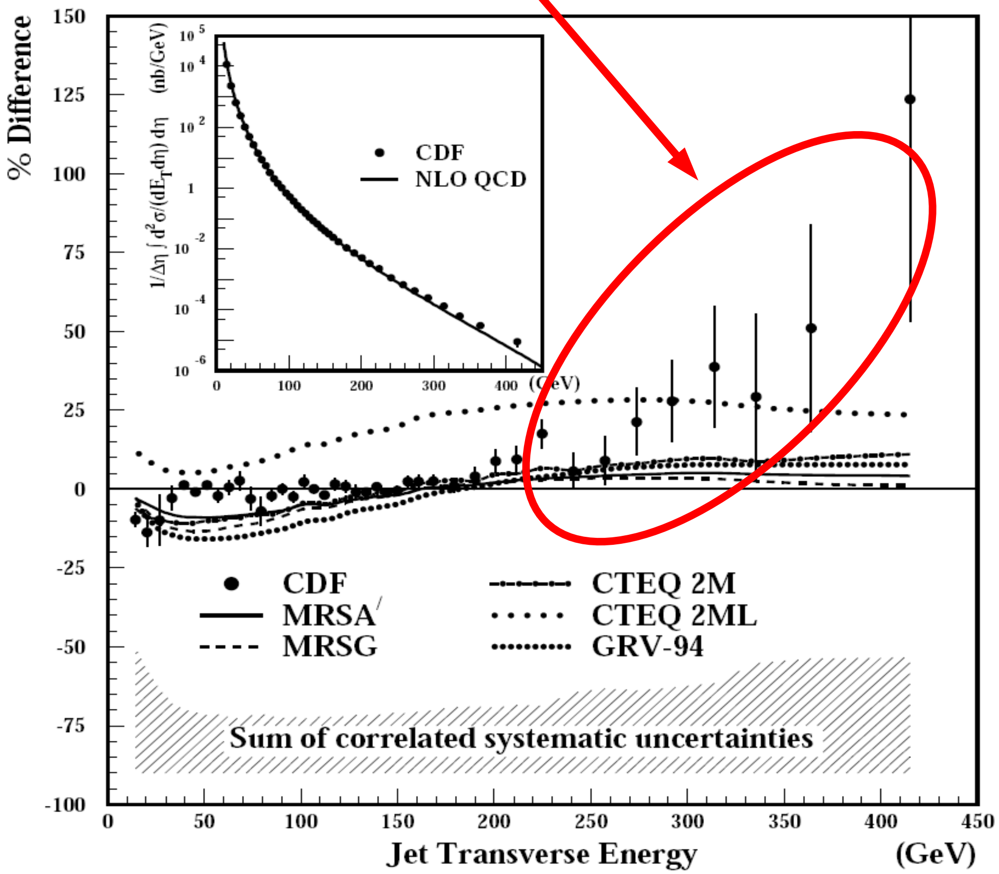
Inclusive Jets at the Tevatron

CDF 1996

CDF 2006

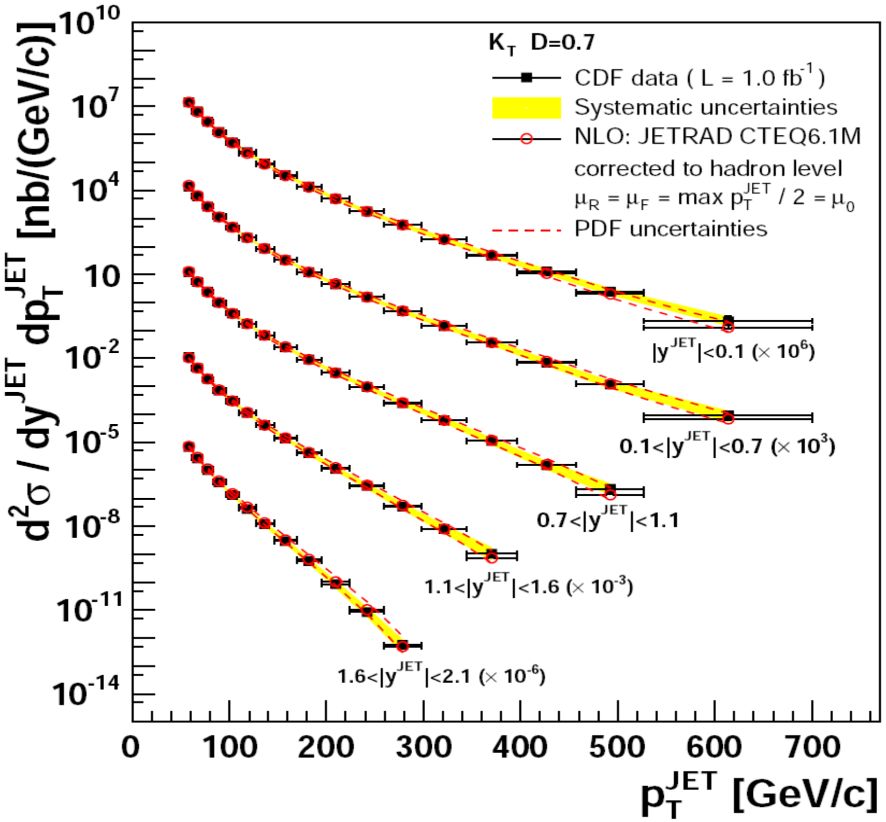
Explained by change in gluon density!

Phys.Rev.Lett. 77 (1996)



CDF Incl. k_T jets, D=0.7

Theory: NLO with CTEQ6.1M



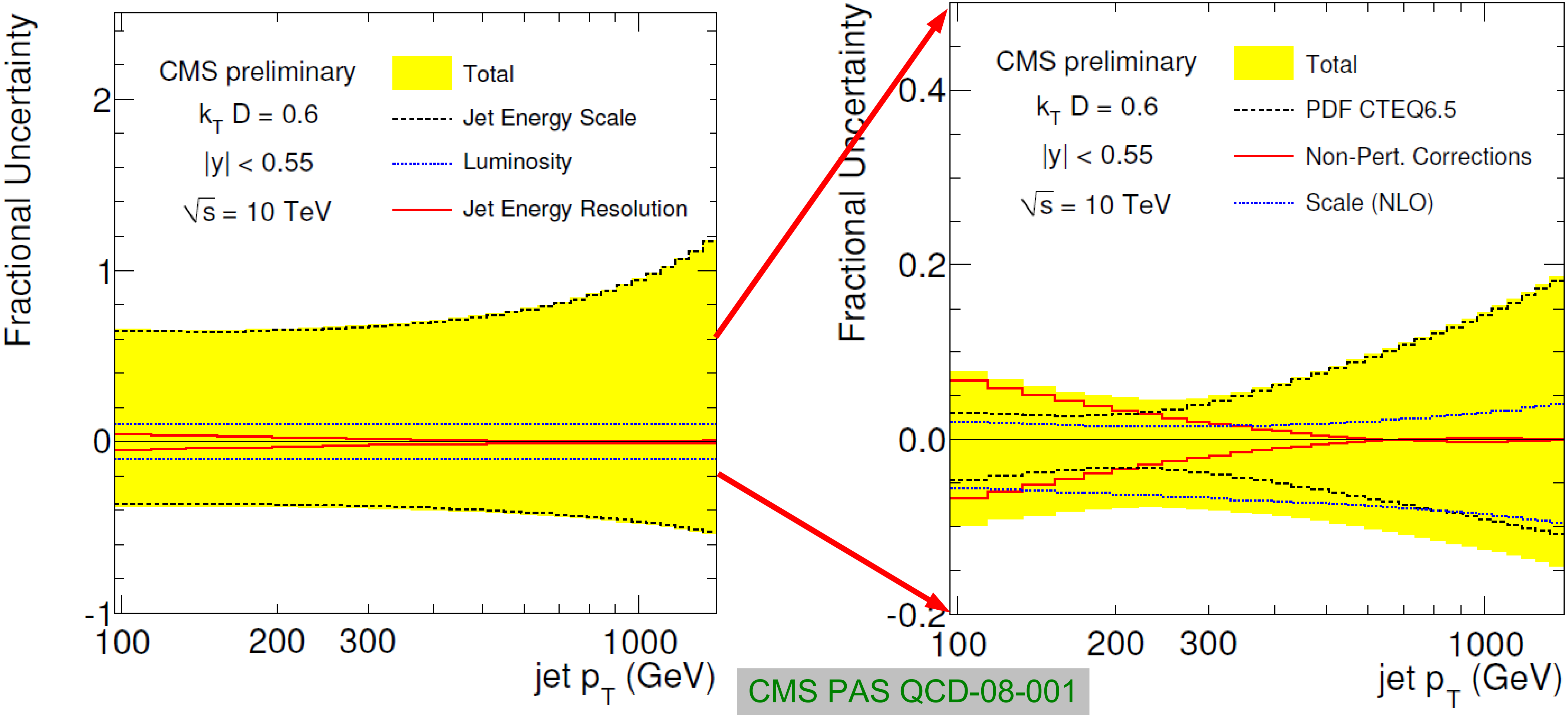
Phys.Rev.D75:092006,2007

Uncertainties at Start-up

k_T, D=0.6, 10 TeV

Experimental Uncertainties

Theoretical Uncertainties

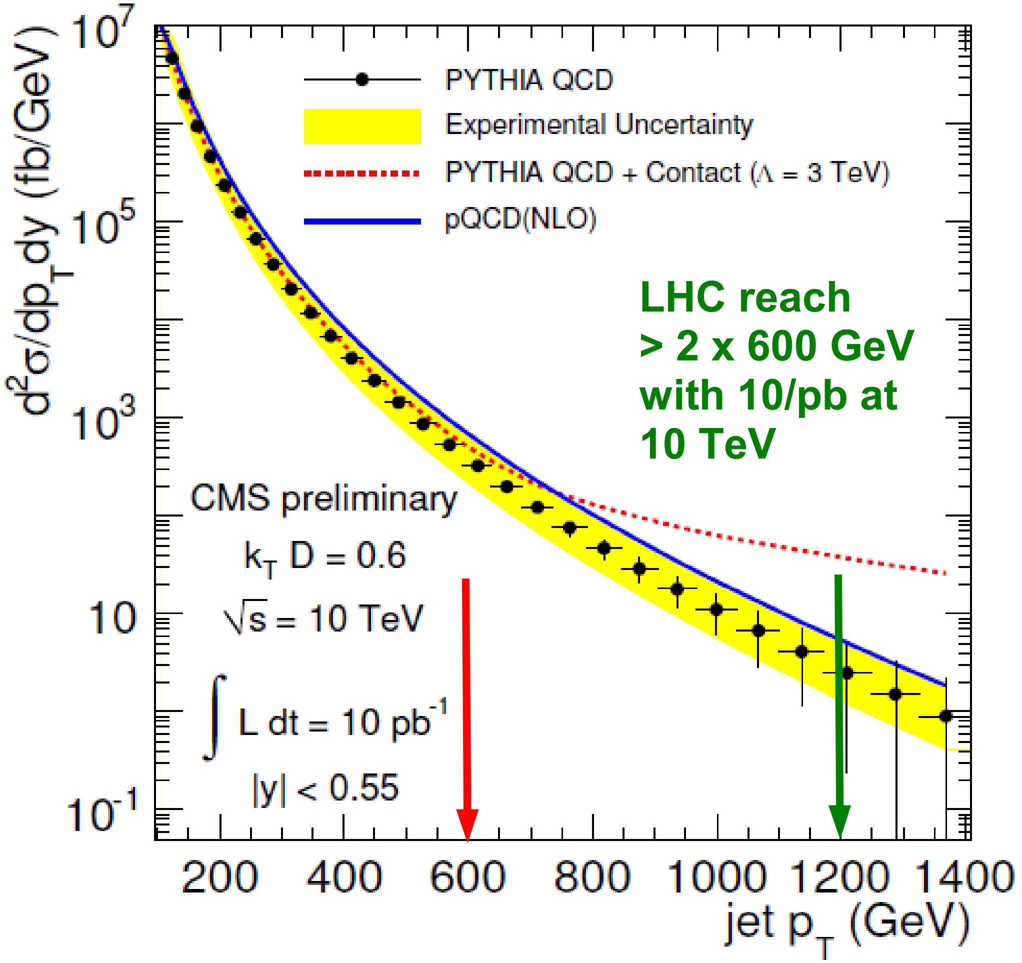


CMS PAS QCD-08-001

Inclusive Jets at the LHC

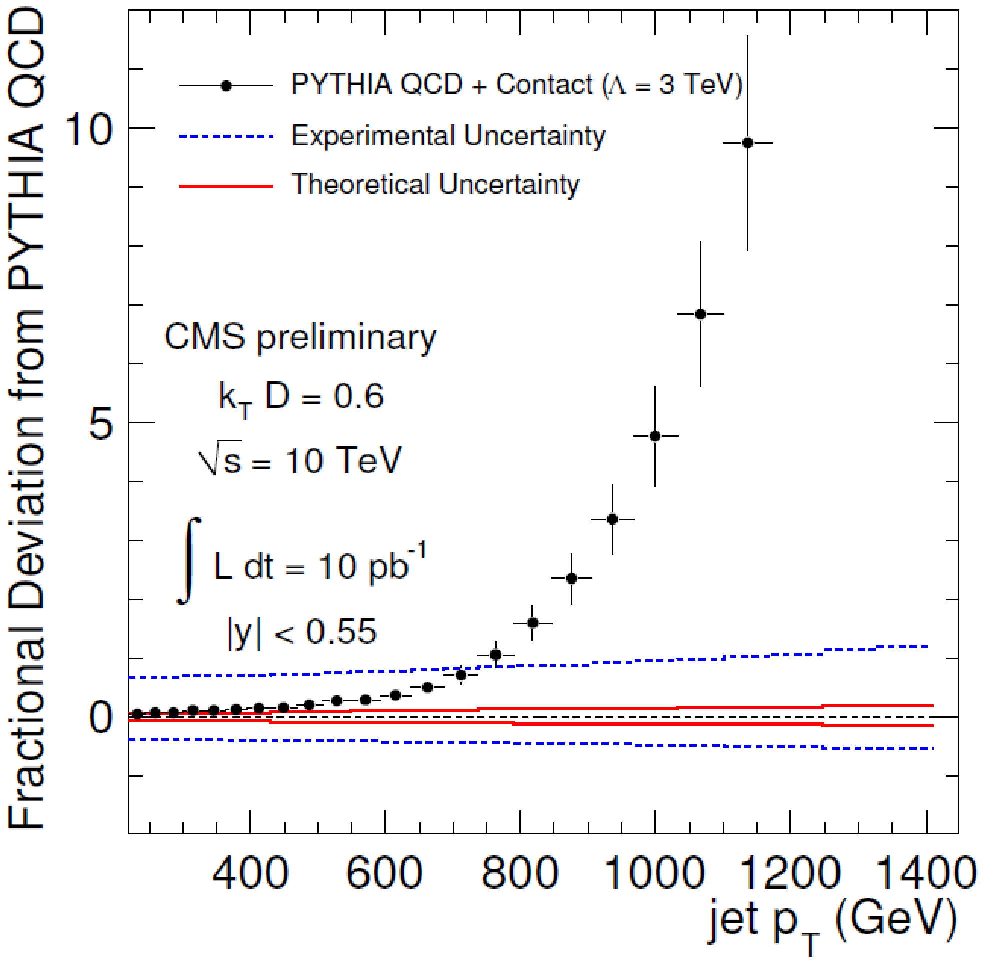
k_T, D=0.6, 10 TeV

Comparison with Contact Interactions



LHC reach
> 2 x 600 GeV
with 10/pb at
10 TeV

Tevatron limit 600 GeV



CMS PAS QCD-08-001C

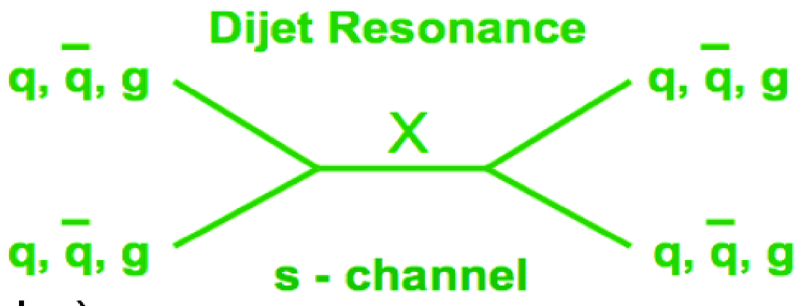
New Physics from Dijets

New Physics with Jets:

- Contact interactions
  - **Resonances**
    - ★ W' & Z' (Grand Unified Theory)
    - ★ E_6 diquarks (D) (Superstrings & GUT)
    - ★ Excited quarks (q*) (Compositeness)
    - ★ RS Gravitons (G) (Extra Dimensions)
    - ★ Colorons (C) & Axigluons (A) (Extra Color)

Need $E_{CMS} > M$

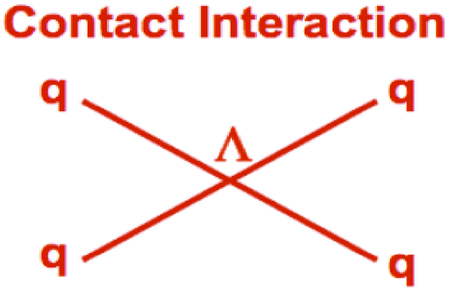
- Di-jet mass distribution


Dijet Resonance

Model	J	Color	Cross Section (pb)					
			M=0.7 TeV		M=2.0 TeV		M=5.0 TeV	
			$\lvert\eta\rvert < 1$	$\lvert\eta\rvert < 1.3$	$\lvert\eta\rvert < 1$	$\lvert\eta\rvert < 1.3$	$\lvert\eta\rvert < 1$	$\lvert\eta\rvert < 1.3$
q*	1/2	Triplet	7.95×10^2	1.27×10^3	9.01	1.36×10^1	1.82×10^{-2}	2.30×10^{-2}
A,C	1	Octet	3.22×10^2	5.21×10^2	5.79	8.82	1.55×10^{-2}	2.04×10^{-2}
D	0	Triplet	8.11×10^1	1.26×10^2	4.20	5.97	4.65×10^{-2}	5.75×10^{-2}
G	2	Singlet	3.57×10^1	5.47×10^1	1.83×10^{-1}	2.60×10^{-1}	2.64×10^{-4}	3.19×10^{-4}
W'	1	Singlet	1.46×10^1	2.37×10^1	3.49×10^{-1}	5.31×10^{-1}	8.72×10^{-4}	1.17×10^{-3}
Z'	1	Singlet	8.86	1.44×10^1	1.81×10^{-1}	2.77×10^{-1}	5.50×10^{-4}	7.26×10^{-4}

- **Contact Interactions**
  - ★ Sensitive to Scale $\Lambda >> \sqrt{s}$!

$$L_{qq} = \frac{Ag^2}{2\Lambda^2}(\bar{q}_L\gamma^\mu q_L)(\bar{q}_L\gamma_\mu q_L)$$

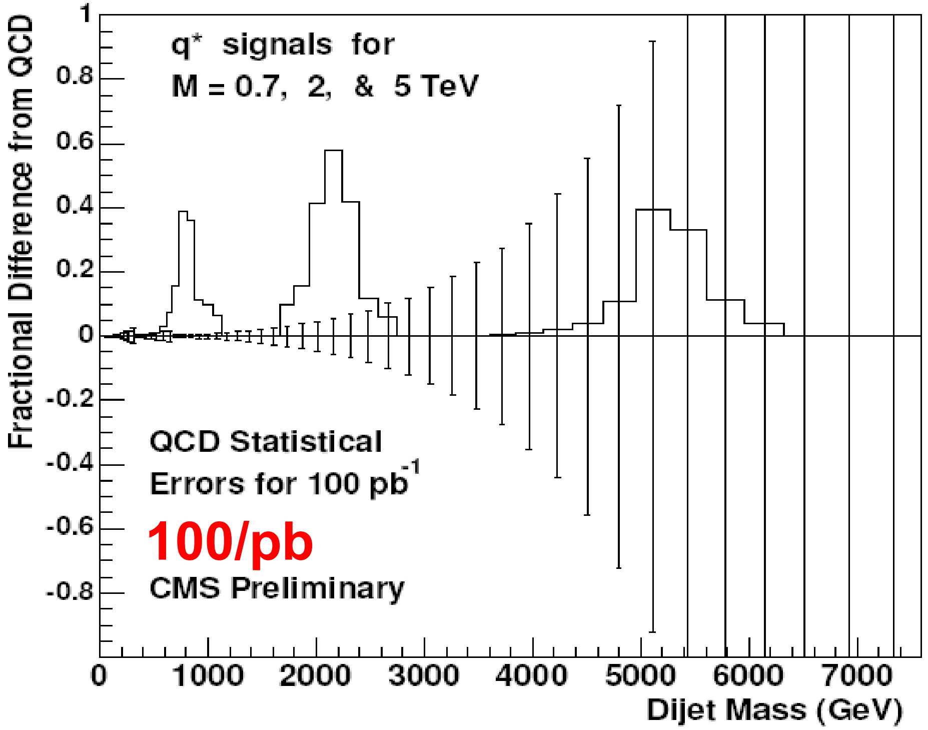

Contact Interaction

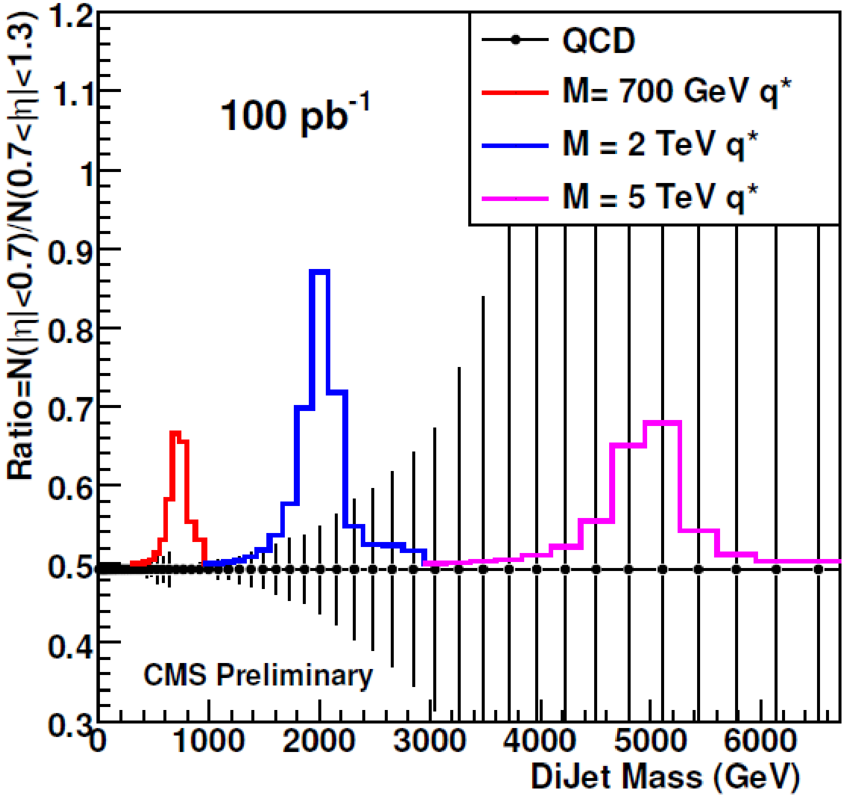
New Physics from Dijets

CMS detector simulation, calorimeter towers, E_{CMS} = 14 TeV

Search for possible signals of q*, visible for M < 2 TeV

(Statistical uncertainty only!)





One means to avoid systematics is by looking into cross section ratios in η

Currently reevaluating this including systematic uncertainties!

CMS PAS SBM-07-001

Dijet Azimuthal Decorrelation

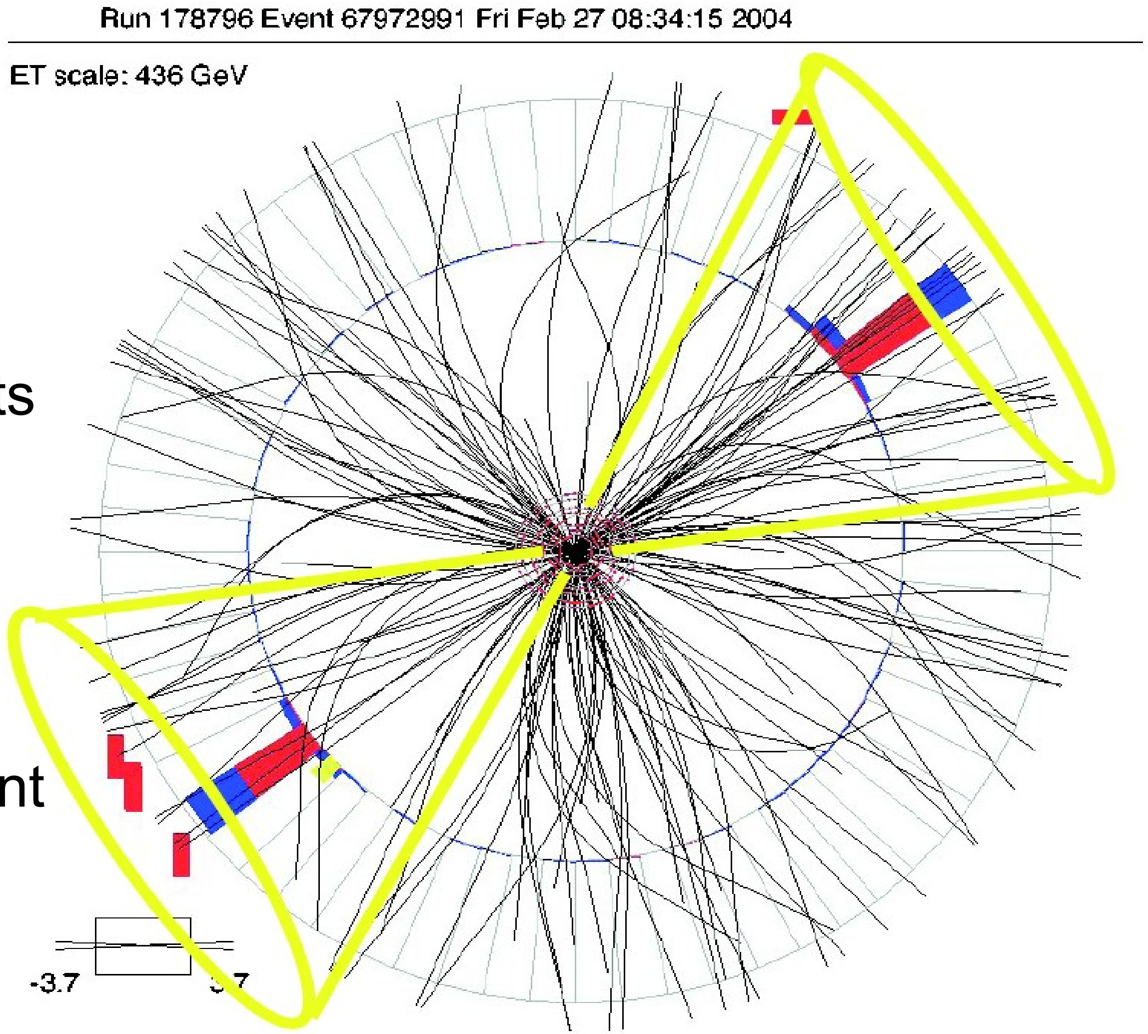
Dijets in pp collisions:

$\Delta\varphi$ dijet = π →
Exactly two jets, no further radiation

$\Delta\varphi$ dijet small deviations from π →
Additional soft radiation outside the jets

$\Delta\varphi$ dijet as small as 2π/3 →
One additional high-pT jet

$\Delta\varphi$ dijet small – no limit →
Multiple additional hard jets in the event



hep-ex/0409040
PRL 94, 221801 (2005)

Dijet Azimuthal Decorrelation

Dijets in pp collisions:

Angular measurement →
  Reduced sensitivity to jet energy scale

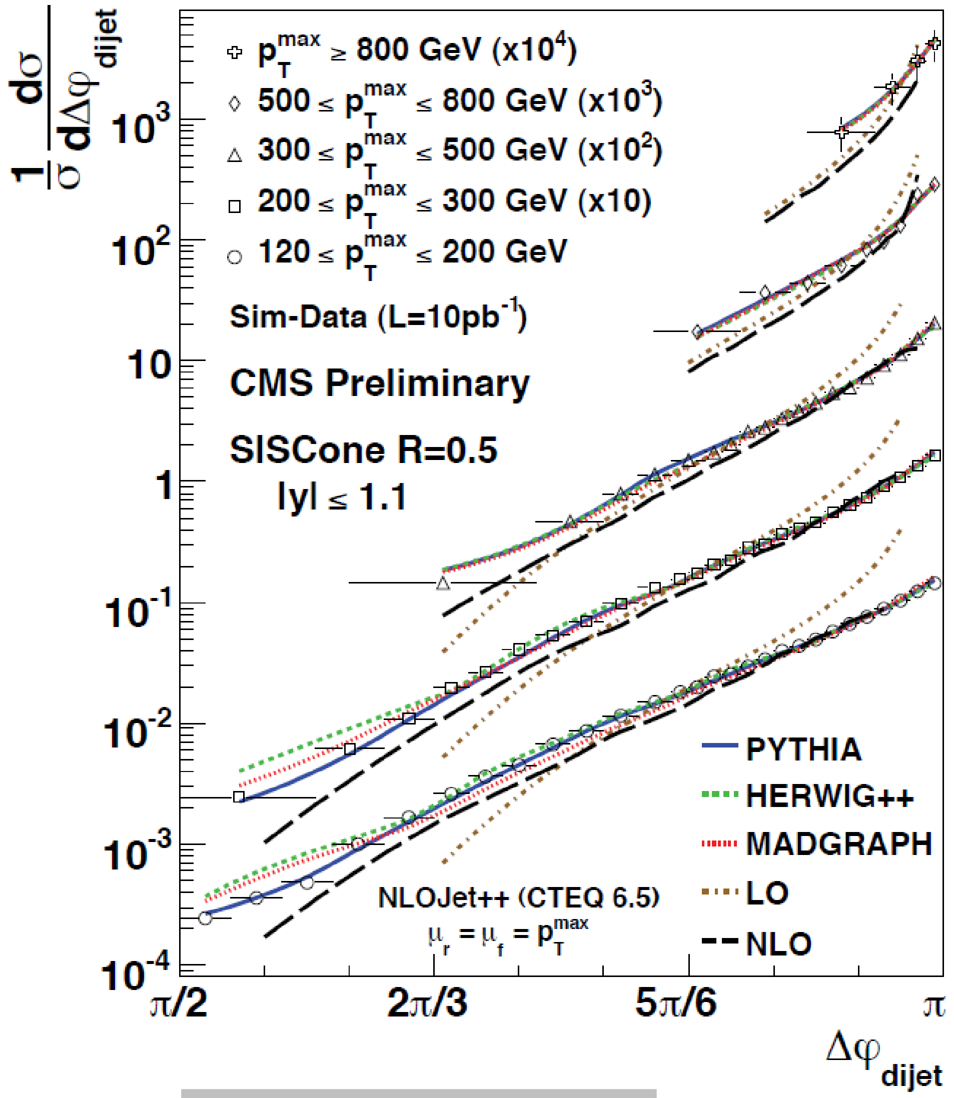
Normalized →
  No dependence on luminosity uncertainty

Also look into:

$$\chi = \exp(|\eta_1 - \eta_2|) = \frac{1+|\cos(\hat{\theta})|}{1-|\cos(\hat{\theta})|}$$

Allows to look for deviations from QCD like scattering due to new physics (extra dimensions, ...)

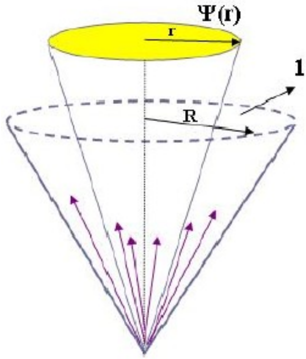
Evaluation in progress



CMS PAS QCD-09-003

Jet Substructure I

Up to now: Try to differentiate between the jet originators, e.g. quarks and gluons

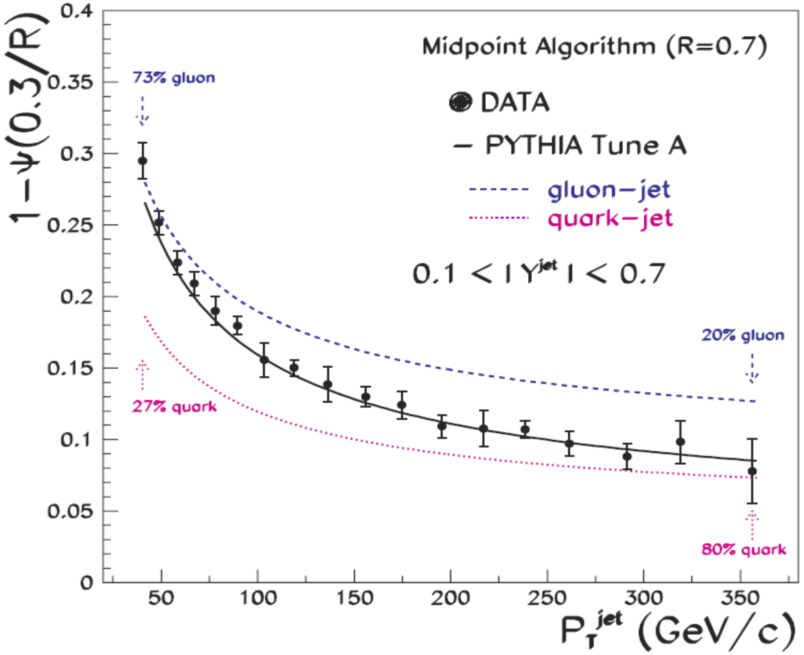


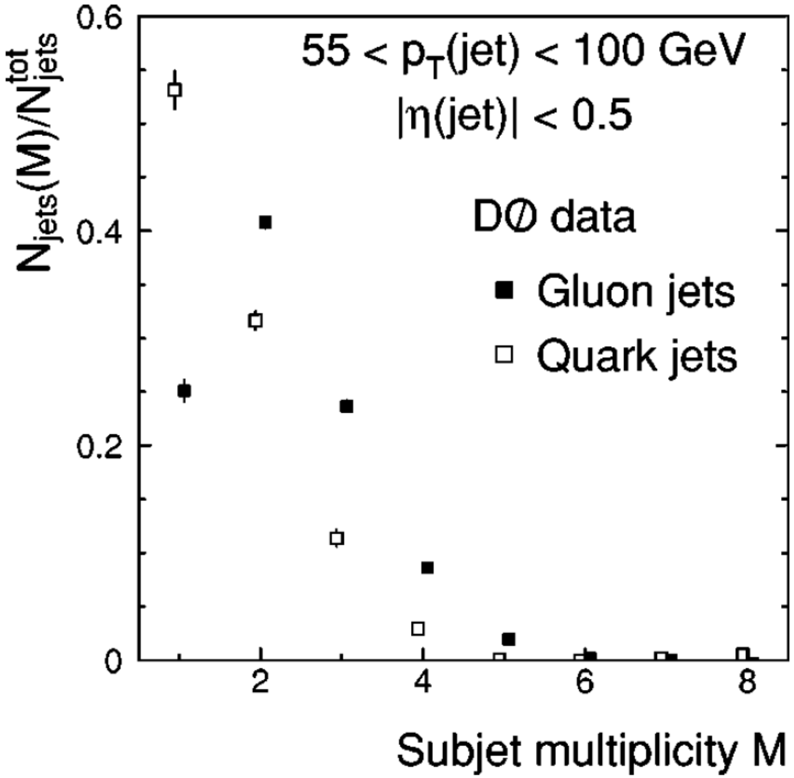
Well-known techniques:

- **Transverse jet profiles (cone)**
- **Subjet multiplicities (k_T)**

$$d_{ij} \equiv \min[p_{T,i}^2, p_{T,j}^2] \frac{\Delta R_{ij}^2}{D^2}$$

CDF , Phys.Rev.D 71 (2005)



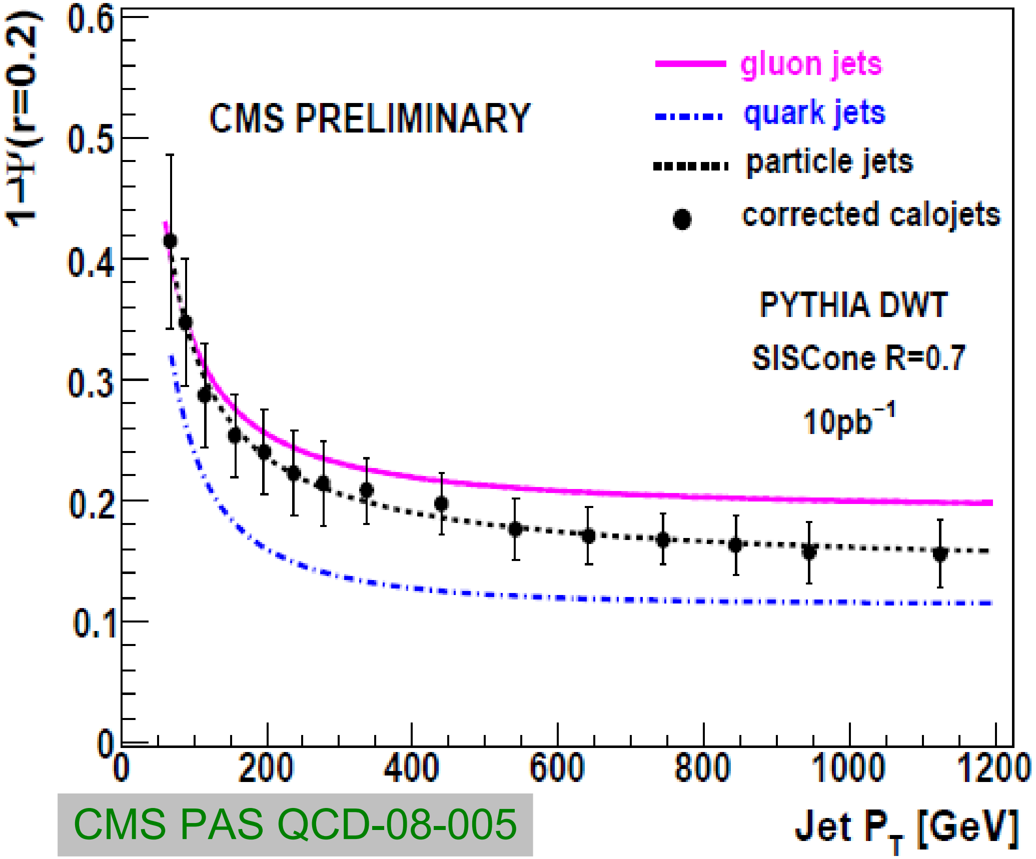


Do, Phys.Rev.D 65 (2008)

Jet Substructure in CMS

CDF like: Integrated jet shape

Calorimeter jets, √s = 14 TeV

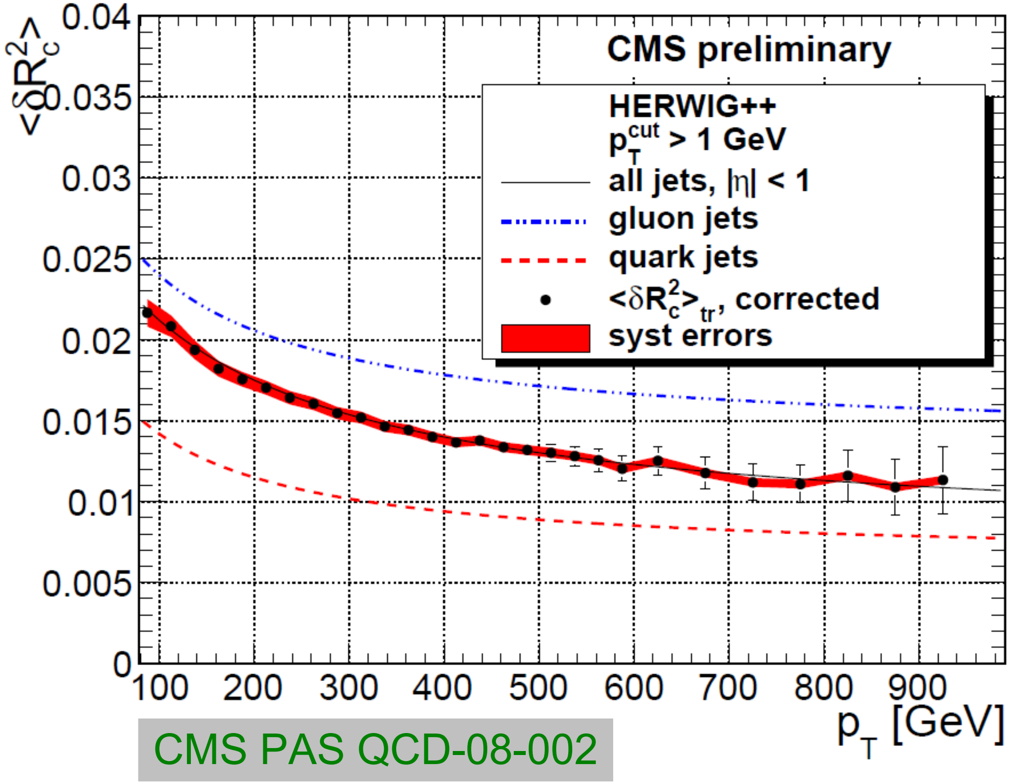


CMS PAS QCD-08-005

New: 2nd radial moment of jet profile

$$\left\langle \delta R^2_{jet} \right\rangle (p_{\mathrm{T}}) = \frac{\sum\limits_{i\in\mathrm{jet}} \Delta R^2(i,jet)\cdot p^i_{\mathrm{T}}}{\sum\limits_{i\in\mathrm{jet}} p^i_{\mathrm{T}}}$$

Track jets, √s = 10 TeV



CMS PAS QCD-08-002

Jet Substructure II

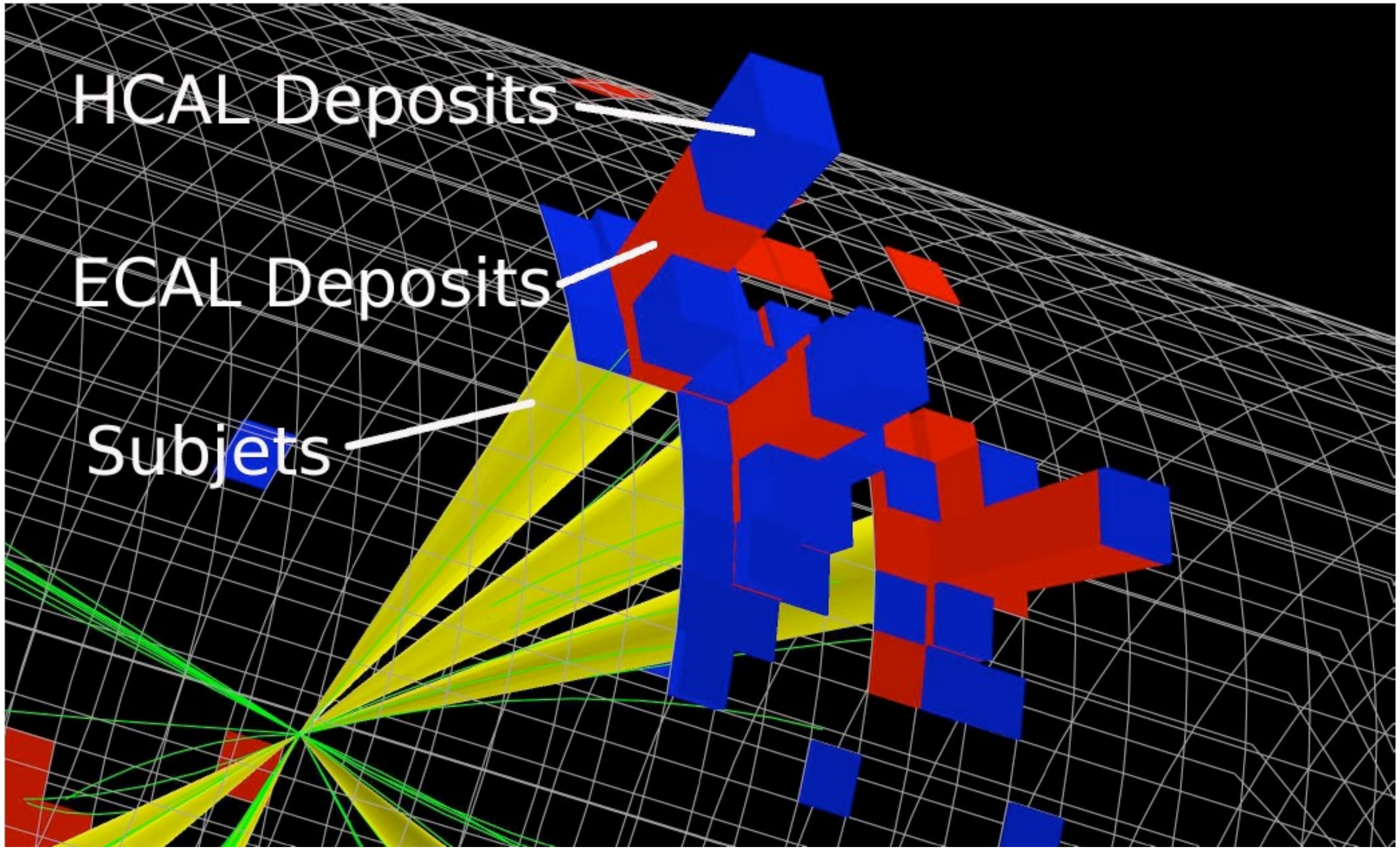
New at LHC: Try to differentiate between “number” of hard jet originators

- **Hadronic decay products of heavy particles at high momenta (boosted Z': 2-prong, tops: 3-prong) end up in the same jet!**
- **Look into k_T subjets, already proposed in** M. Seymour, Z.Phys.C62, 1994
- **Recently a lot of interest in jets of boosted heavy particles, see**

  Butterworth et al., PRD65, 2002; Fitzpatrick et al., JHEP07, 2007; B. Holdom, JHEP03, 2007; ...
- **Could open up hadronic decay modes for discoveries ...**
- **Newer theoretical paper on this:** Almeida et al., PRD79, 2009
- **Quick estimate of experimental feasibility:**
  - **Smallest jet sizes considered: R = 0.4**
  - **=> Jet area ≈ πR^2 ≈ 0.50 => #towers ≈ 0.50 / (0.1x0.1) = 50**
- **ATLAS colleagues bit more active, catching up =>**

Boosted Tops 1

- Example analysis looking for top jets with p_T of >≈ 600 GeV in signal sample Z' → ttbar → hadr. with $M_{Z'}$ = 2 TeV vs. QCD jets at similar p_T
- Use Cambridge/Aachen algorithm to resolve subjets, R = 0.8
- Gain stat. from ≈ 68% of hadr. W decays
- Efficiency for top jets: **46%**
- Reject non-top jets: **98%**
- Example has 800 GeV

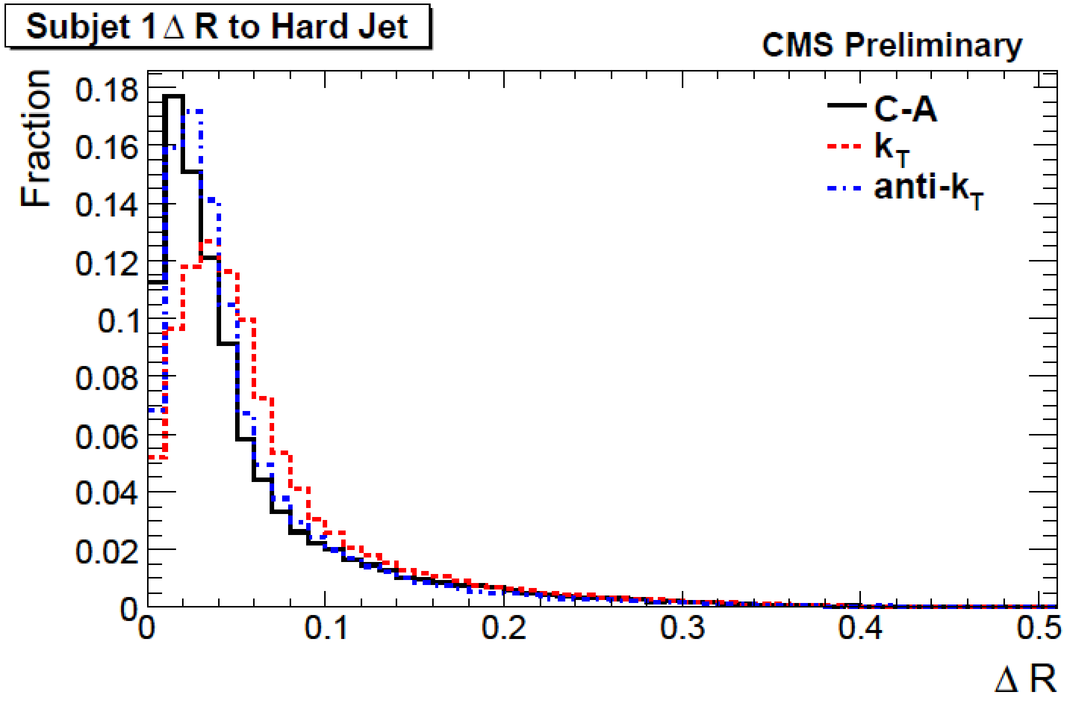


Kaplan et al., PRL101, 2008
CMS PAS JME-09-001

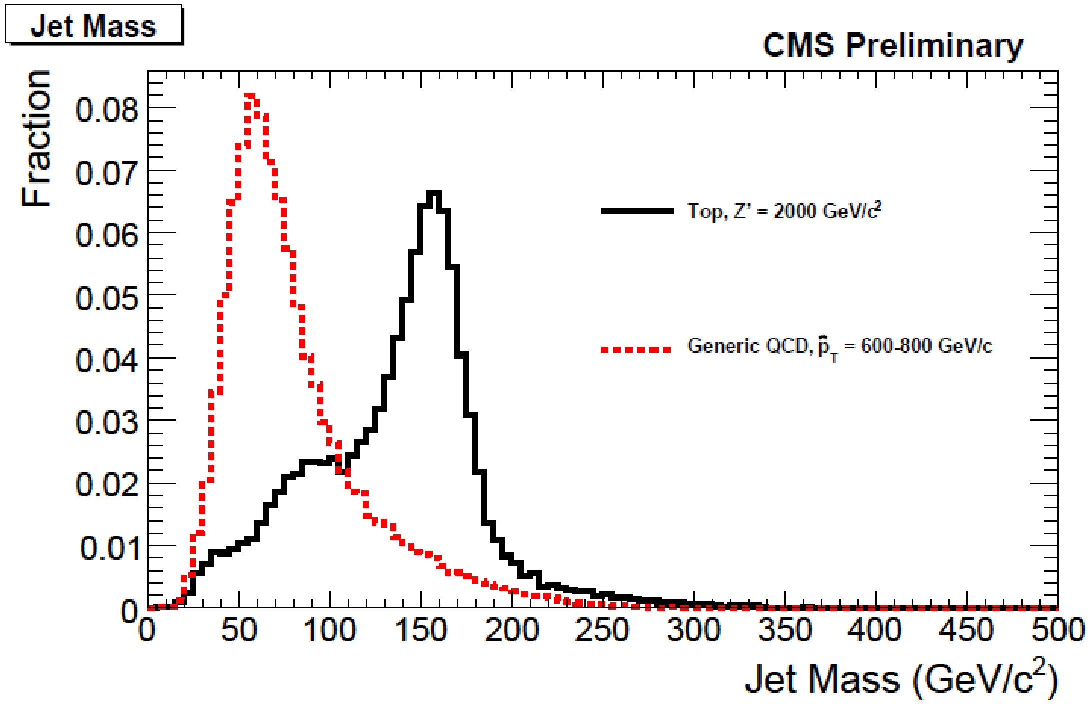
Boosted Tops 2

CMS detector simulation, calorimeter towers, E_{CMS} = 10 TeV

Distance of highest pT subjet to jet axis:
Smallest for Cambridge/Aachen
(Jet pT similar, jet masses larger for kT)



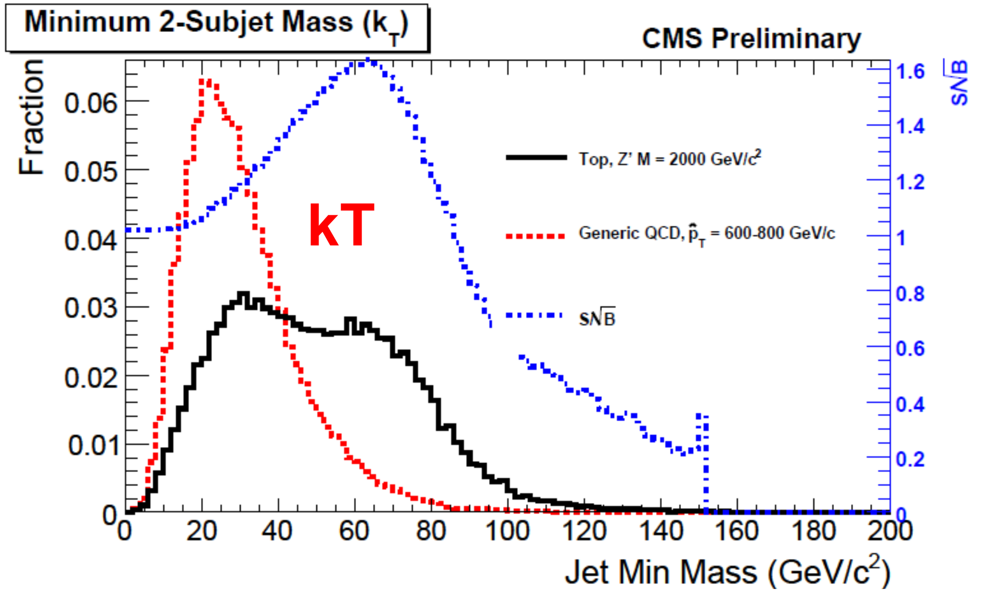
Comparison of jet masses for Z' and QCD:
For Cambridge/Aachen



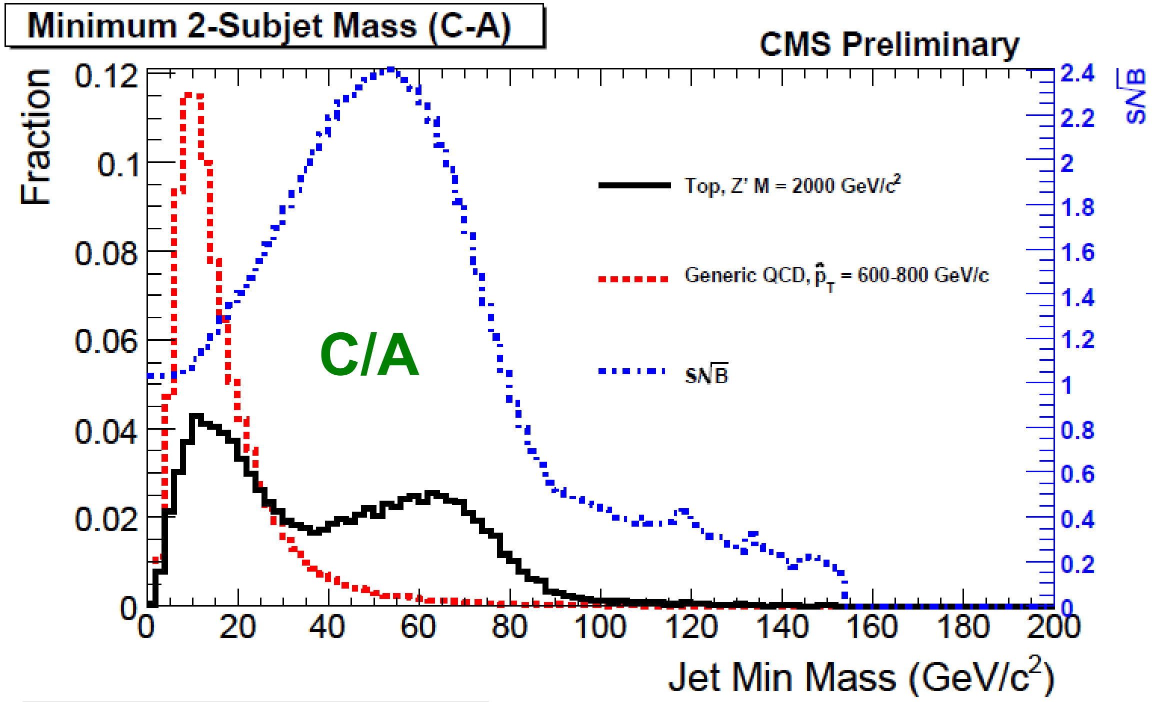
CMS PAS JME-09-001

Boosted Tops 3

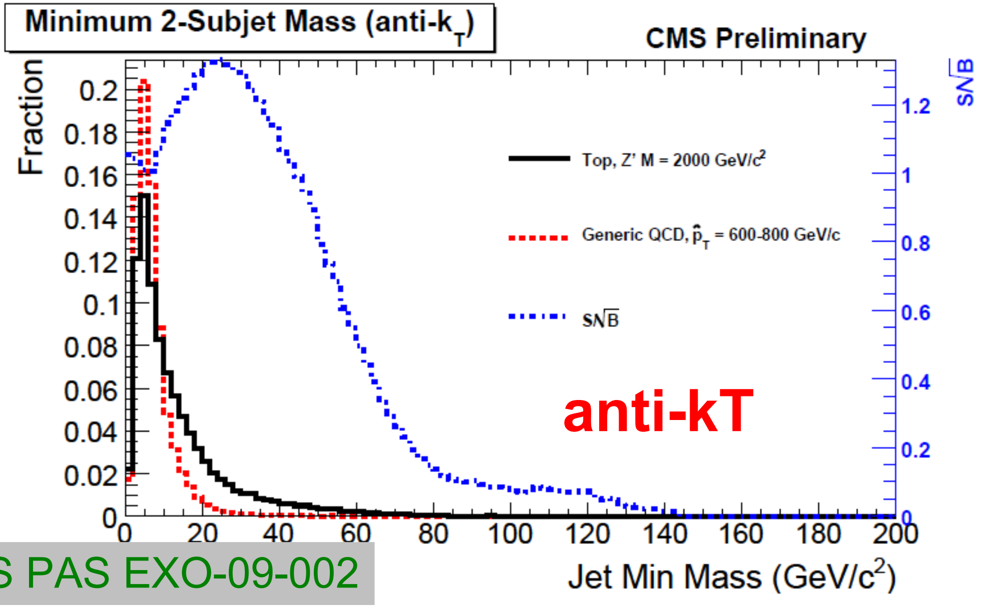
- Undo C/A clustering sequence twice requiring pT of each subjet > 0.05 pT of “top”-jet
- Take minimal mass combination of leading 3 subjets => feature at $\approx M_W$



Minimum 2-Subjet Mass (k_T)



Minimum 2-Subjet Mass (C-A)



Minimum 2-Subjet Mass (anti-k_T)

CMS PAS JME-09-001

Method applied in: CMS PAS EXO-09-002

Outlook

- **At the LHC we will go beyond Tevatron limits and explore unknown territory in QCD and new physics**
- **LHC is also a superb laboratory for all kind of jet physics**
- **Some tough experimental systematics to deal with, but combining detector parts will help in the long run (jets+tracks, ...)**
- **Since the jet energy corrections are difficult to develop, experimentalists prefer to use only a small choice of them**
- **However, which jet algorithm is optimal for what purpose? I think we have still some things to learn ...**
- **New measurements are just ahead!**

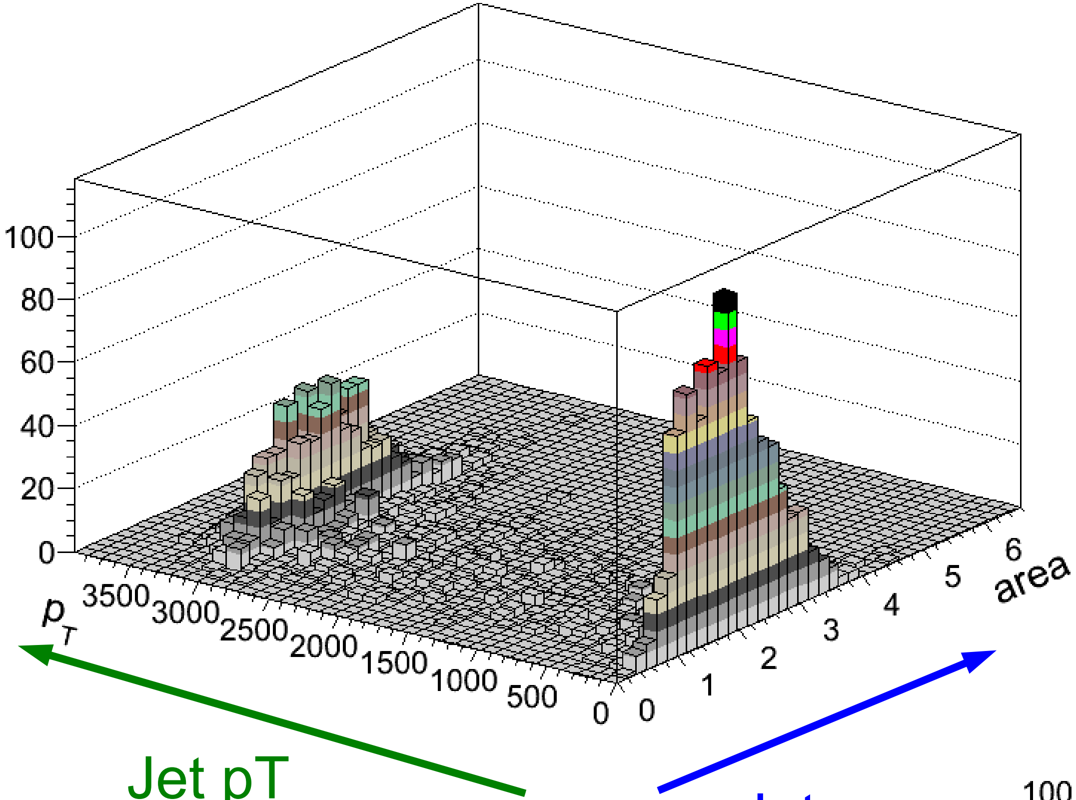
Thanks to the organizers for inviting me to this workshop
in Florence as experimentalist of the week.

Backups

Jet Areas vs. Jet pT

Pythia QCD high pT particle jets
3000 < pT_hat/GeV < 3500

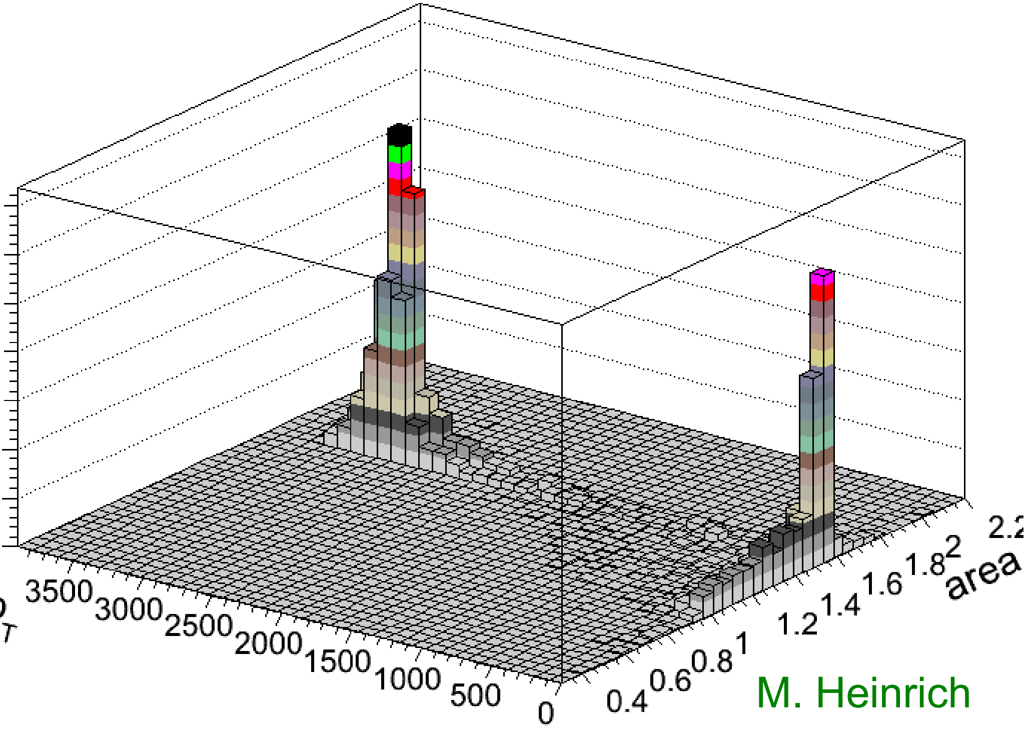
k_T, R = 0.7



Jet pT

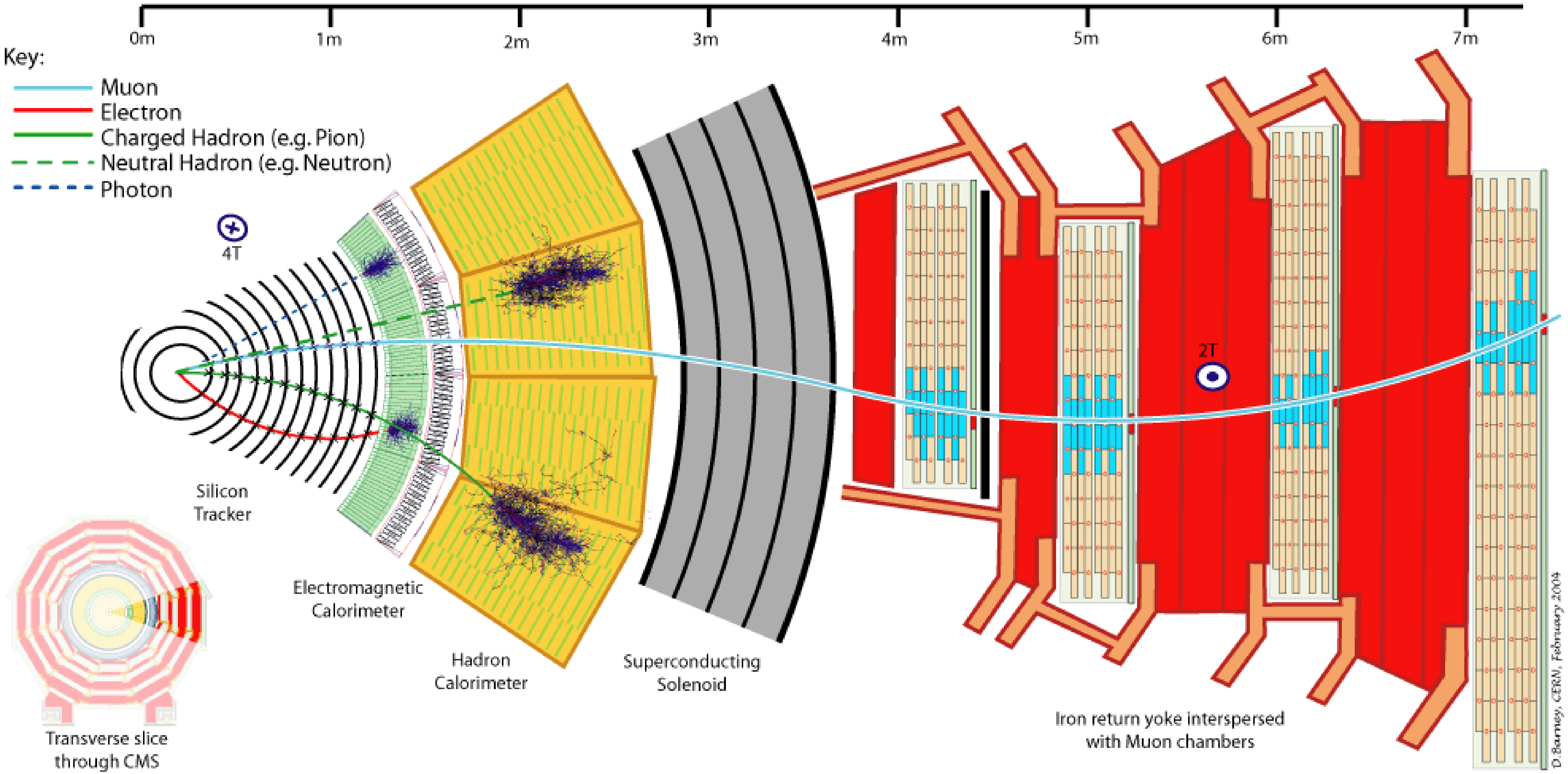
Jet area

anti-k_T, R = 0.7

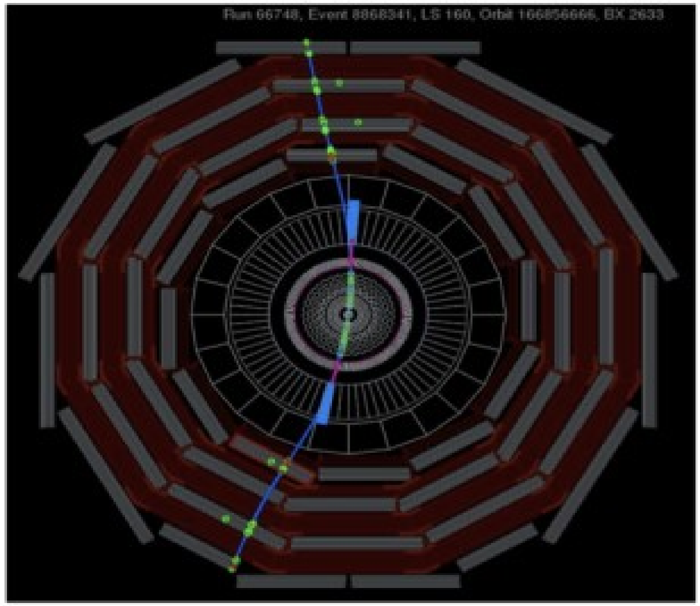


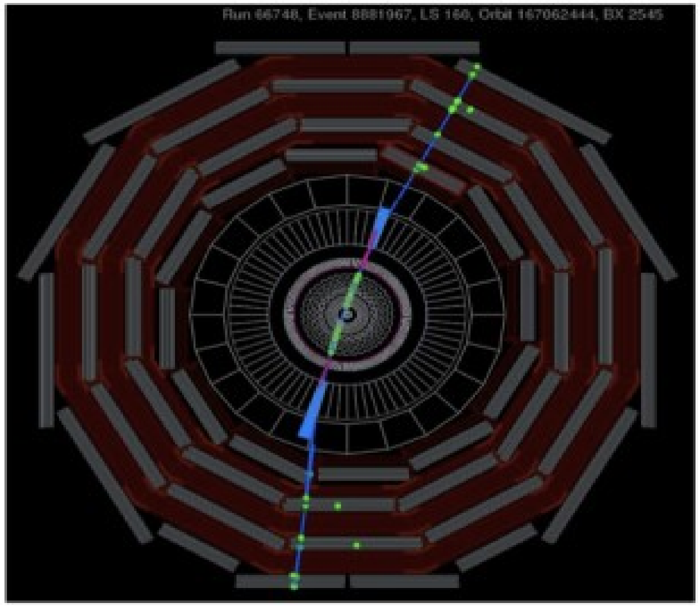
M. Heinrich

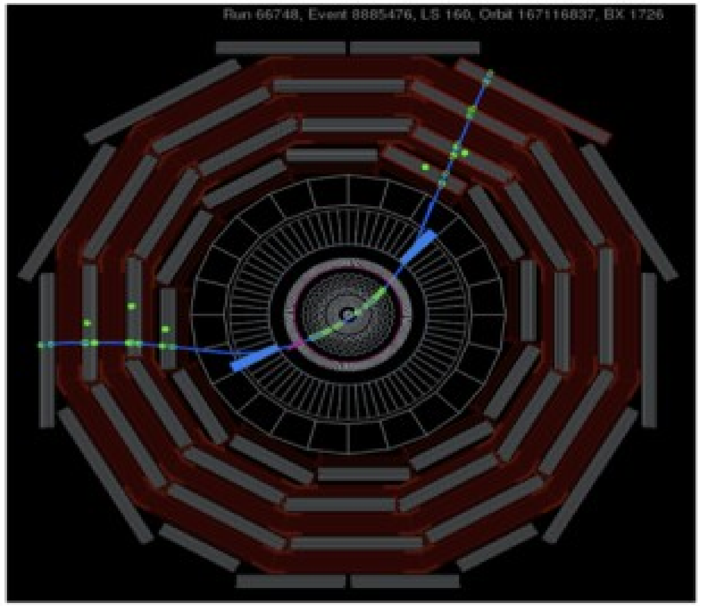
Transverse Slice through CMS

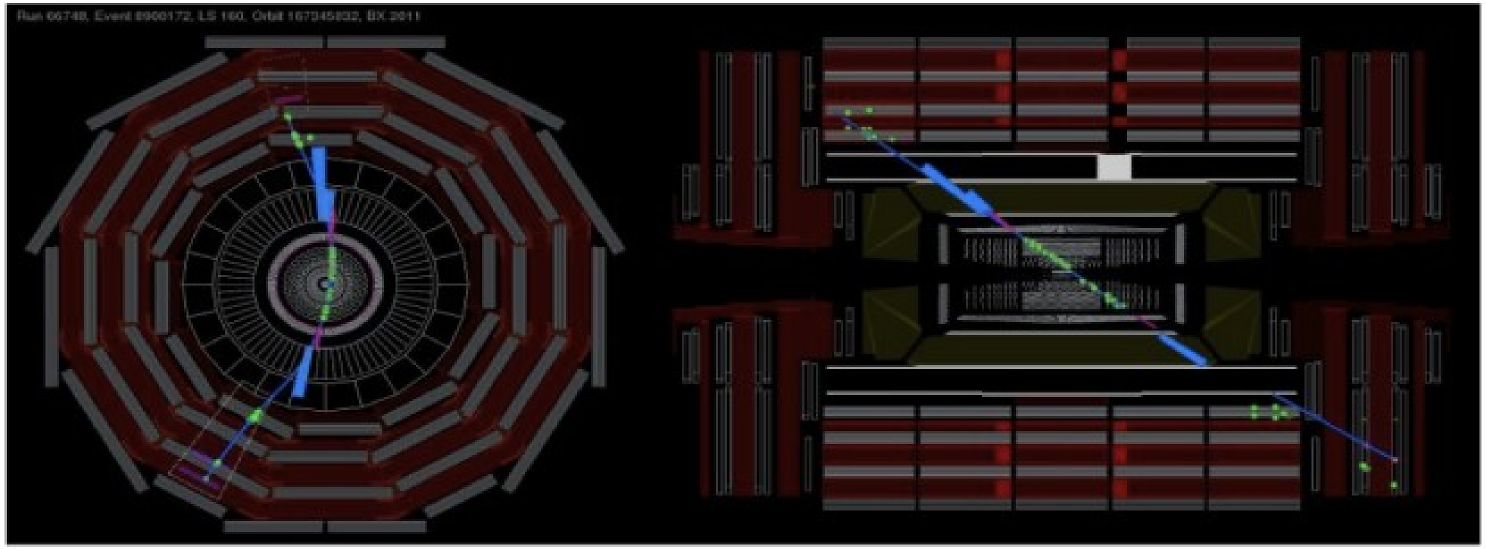


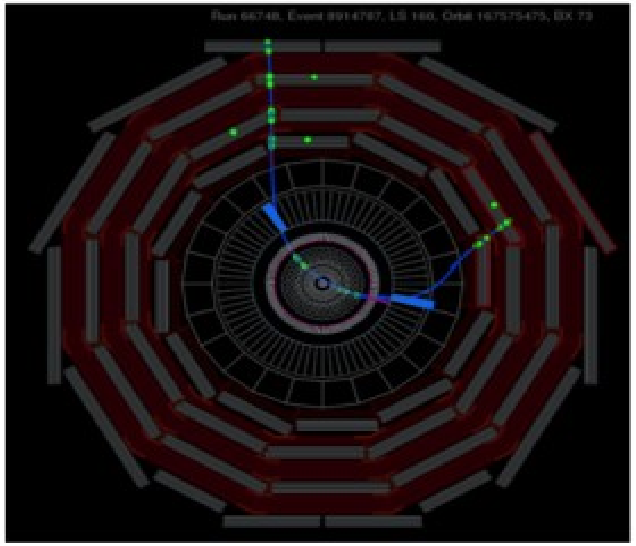
> One Billion Cosmic Myons



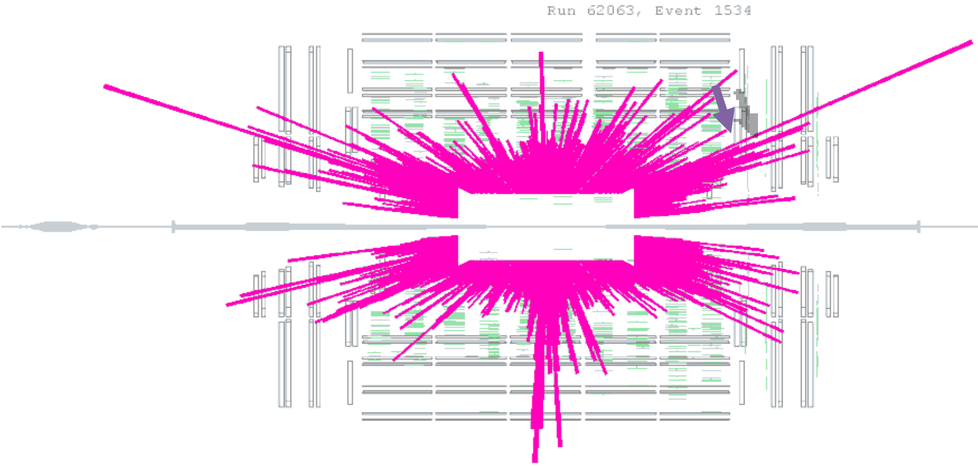








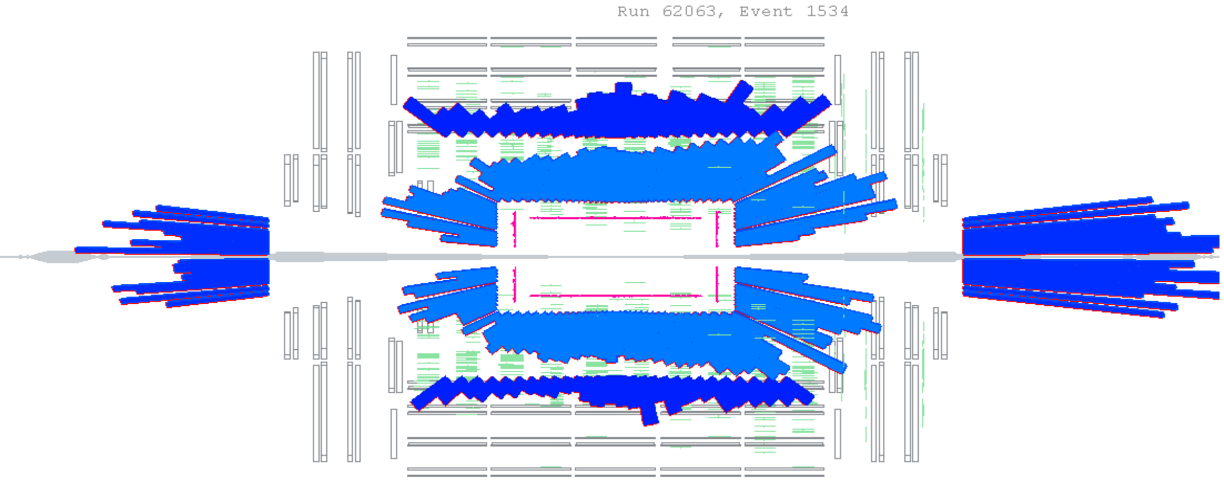
Splash Events



3.1/0.2 fps

ECAL Energy

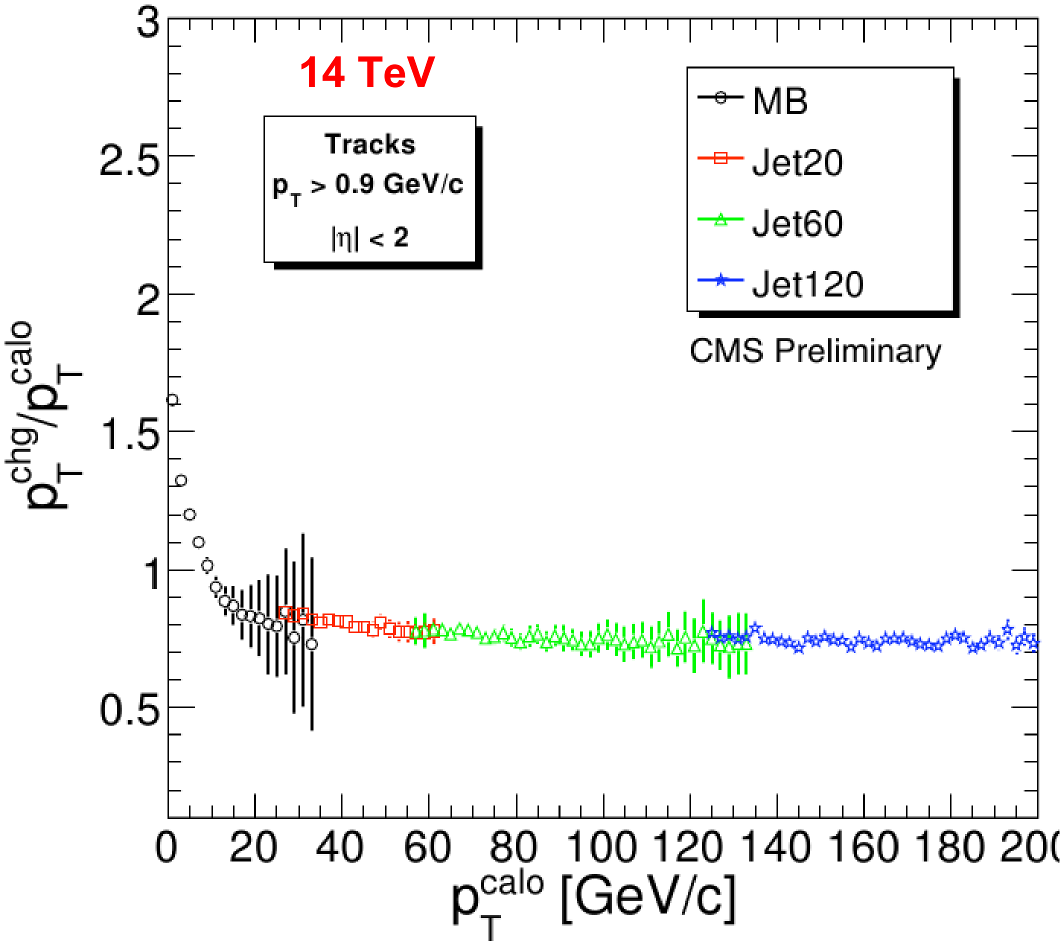
HCAL Energy



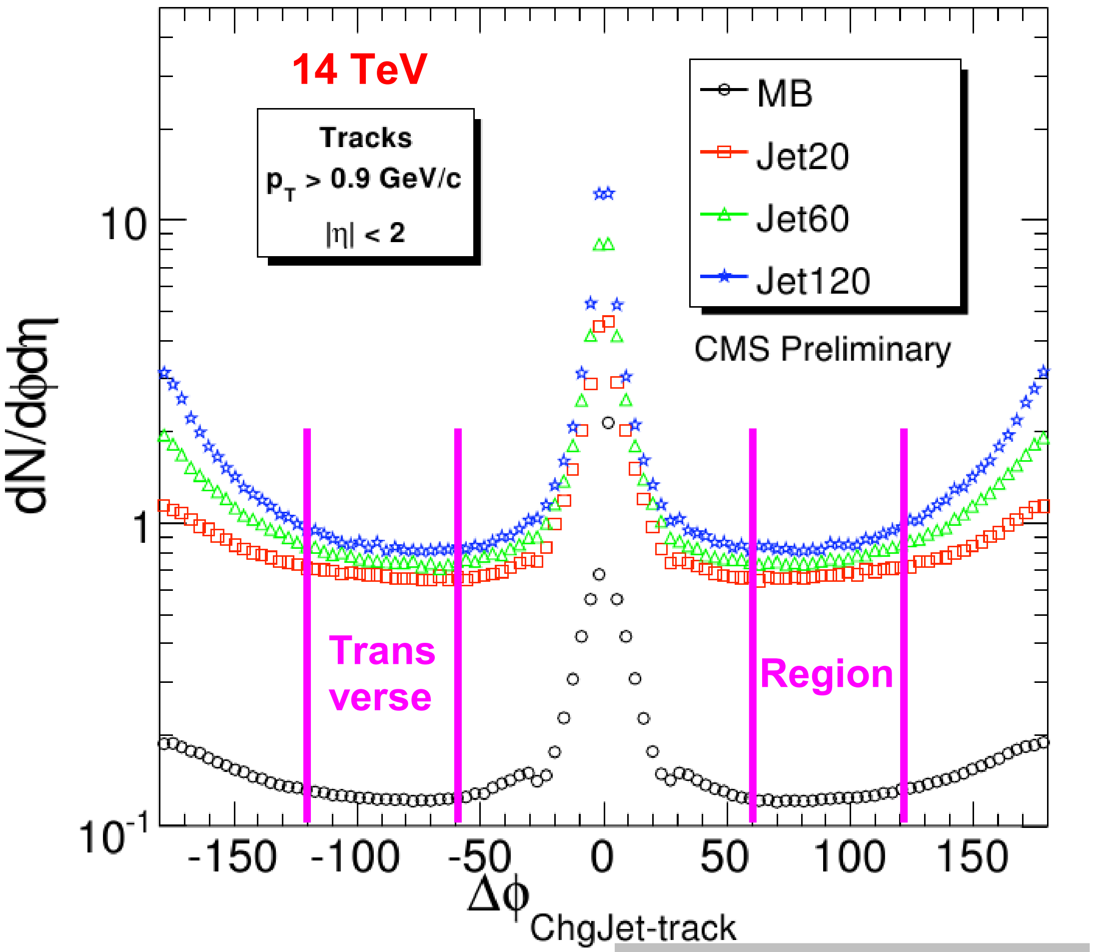
Shots of proton beam (clockwise, $2\cdot10^9$) onto a collimator 150m upstream of CMS

The Underlying Event

Mix of contributing MinBias and calorimetric jet triggers



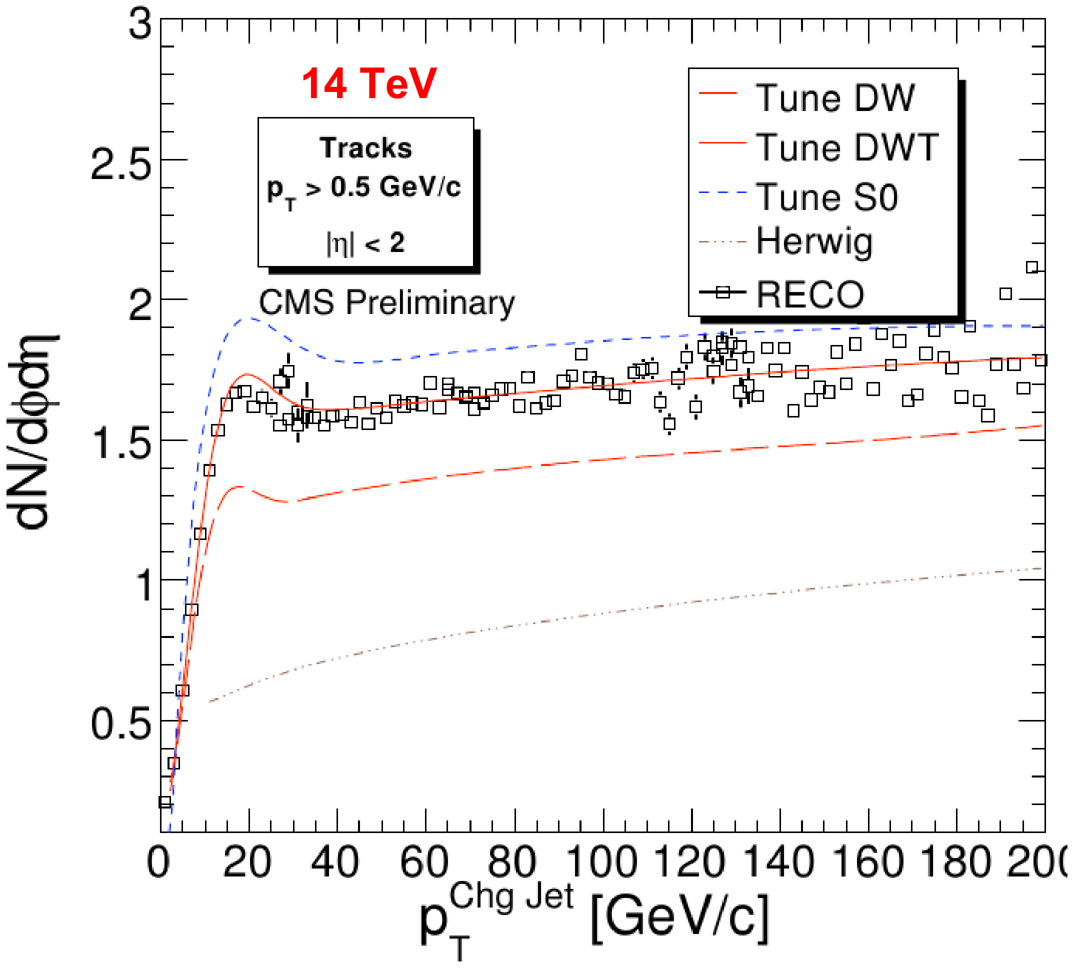
Decomposition of trigger contributions to charged particle density in ΔΦ plane



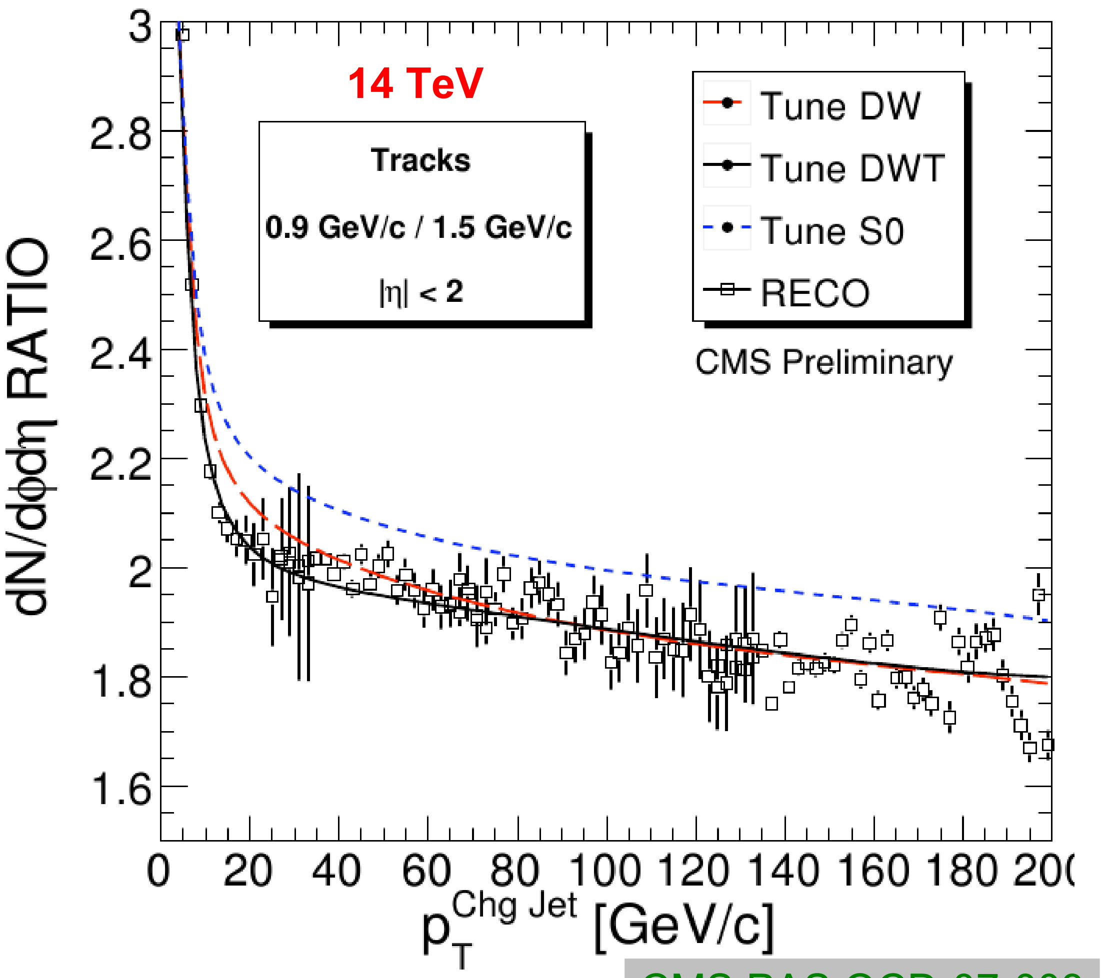
CMS PAS QCD-07-003

The Underlying Event

Increase sensitivity with tracks from p_T > 0.5 GeV instead of > 0.9 GeV



Decrease systematic effects with ratio, but with similar systematic → 0.9 / 1.5

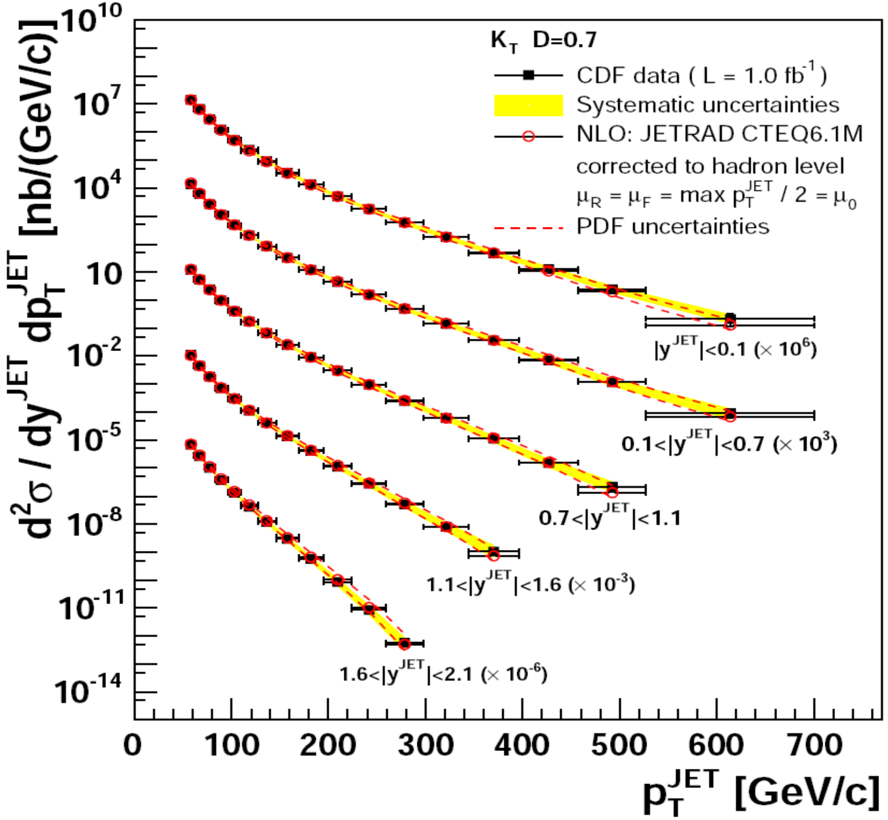


CMS PAS QCD-07-003

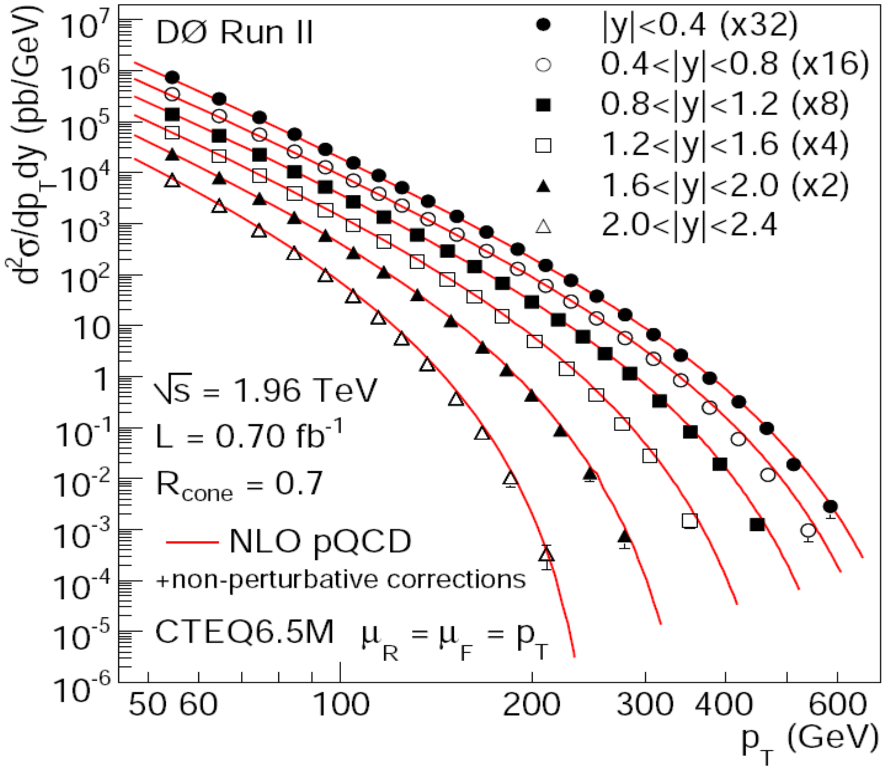
Inclusive Jets at the Tevatron

CDF Incl. k_T jets, D=0.7
Theory: NLO with CTEQ6.1M

Phys.Rev.D75:092006,2007



D0 Incl. MidPoint cone jets, R=0.7
Theory: NLO with CTEQ6.5M



arXiv:0802.2400 [hep-ex]

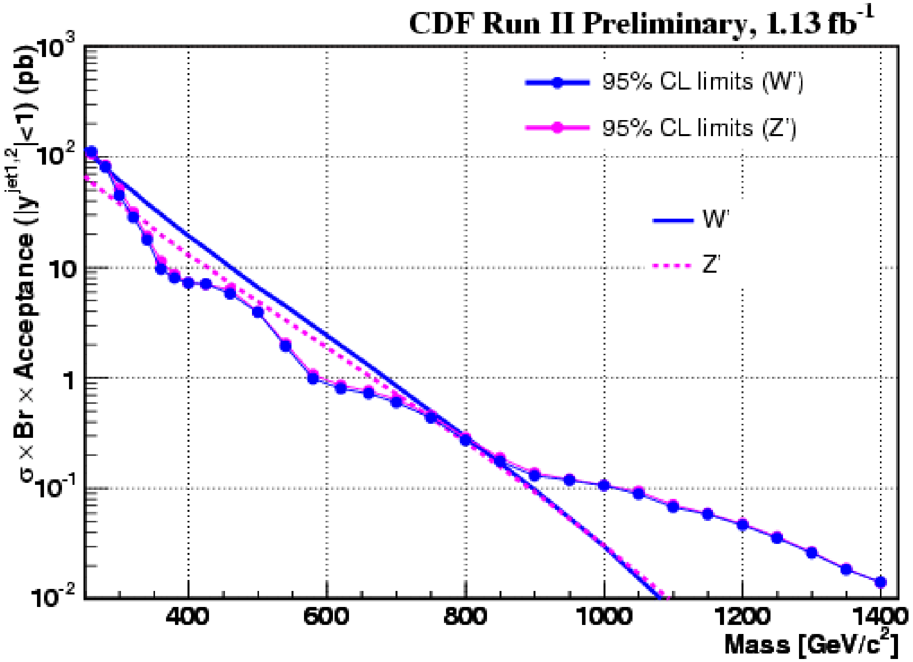
Tevatron Limits

Tevatron limit on contact interaction scale (qqqq): > 2.4 - 2.7 TeV

Dijet resonance search

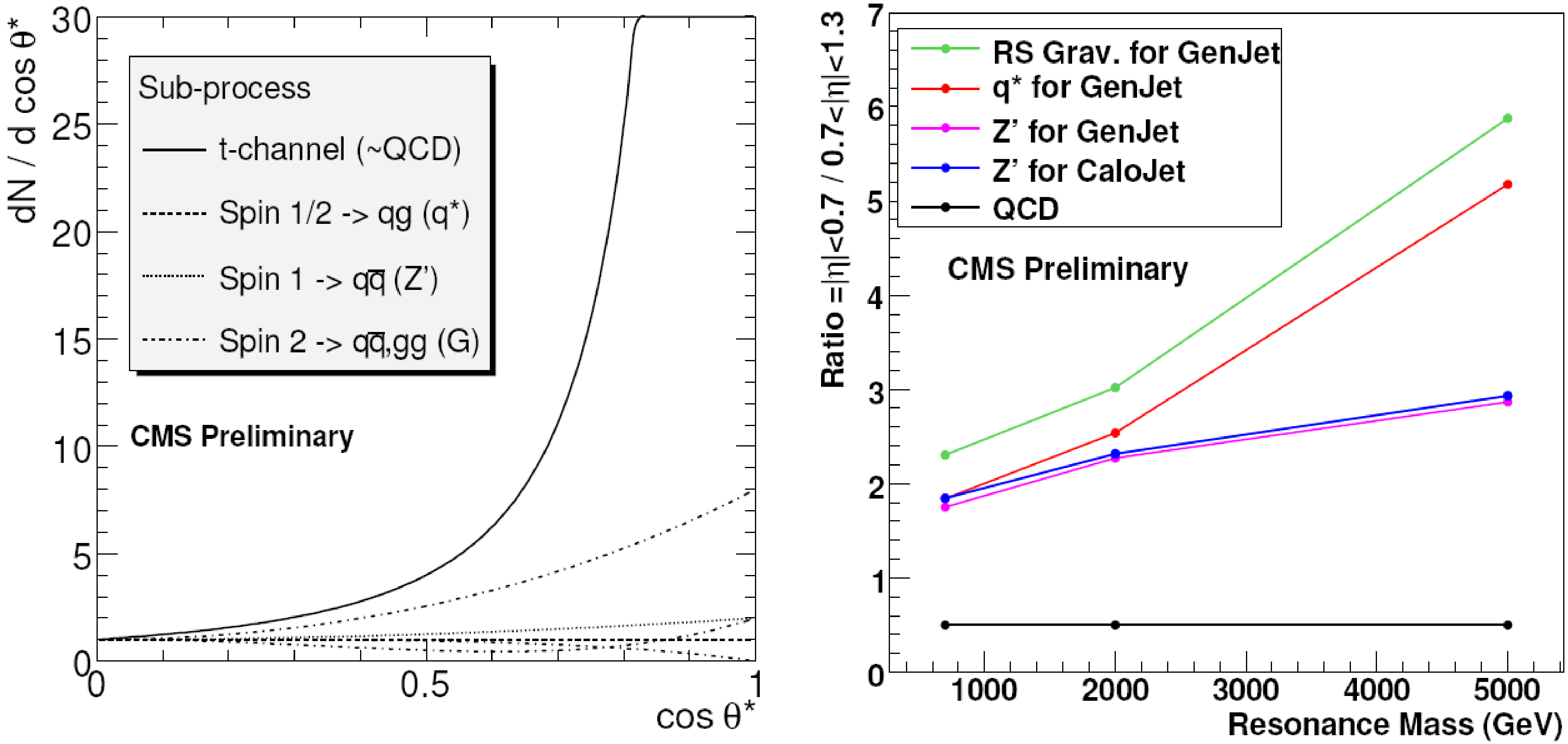
Resonance	Excluded (GeV)	Resonance	Excluded (GeV)
A or C	260 - 1250	D	290 - 630
ρ_{T8}	260 - 1110	W'	280 - 840
q*	260 - 870	Z'	320 - 740

CDF Preliminary 03/2008



Exclusion limits for W' and Z'

Dijet Ratios



- **Sensitivity to new physics from dijet x section ratios in pseudo-rapidity**
- **Reduced sensitivity to jet energy scale**

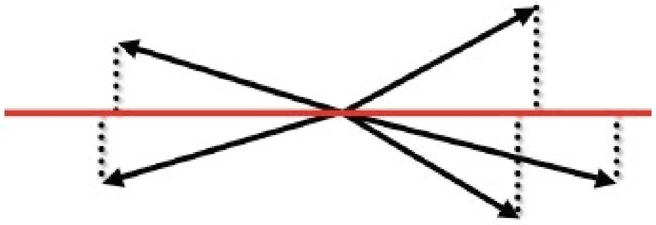
CMS PAS SBM-07-001

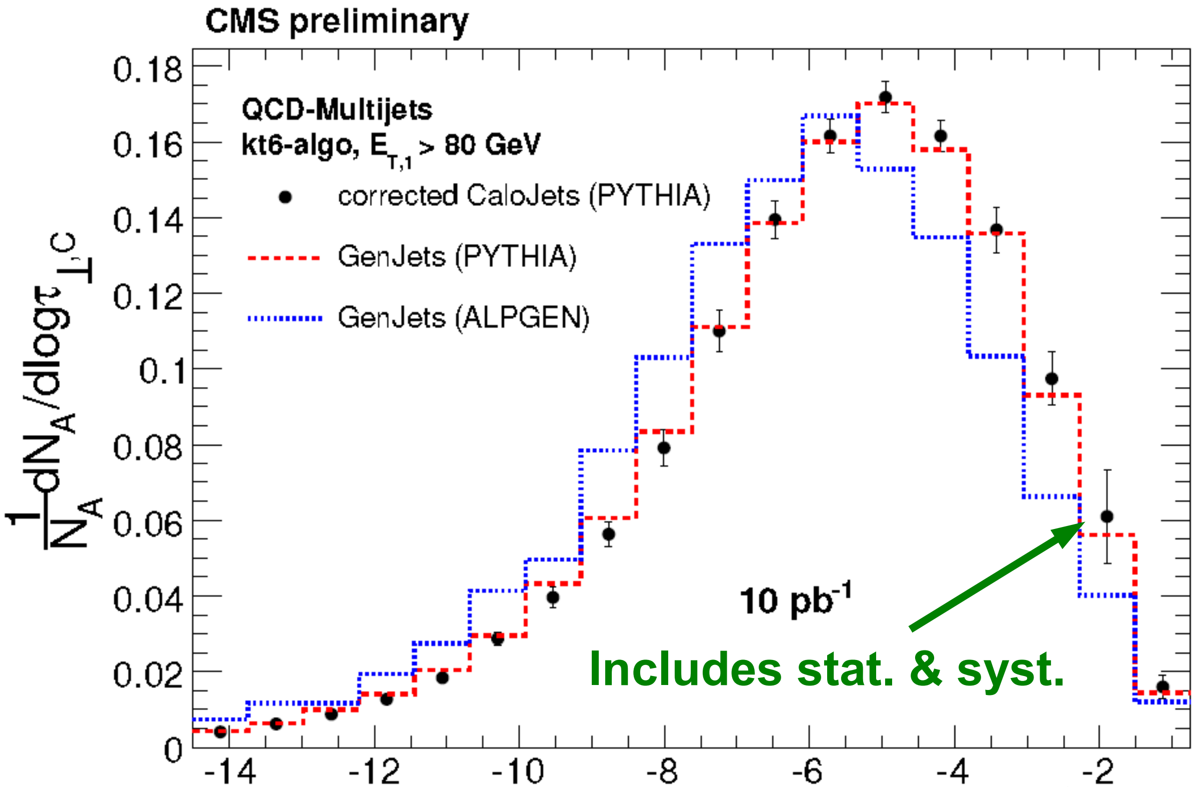
Event Shapes

Definition:

Transverse global Thrust
(k_T jets, $E_{T,1} > 80$ GeV, $E_{T,\mathrm{all}} > 60$ GeV)

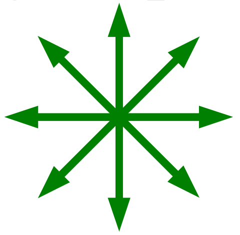
$$T_{\perp,g} \equiv \max_{\vec{n}_T} \frac{\sum_i |\vec{p}_{\perp,i} \cdot \vec{n}_T|}{\sum_i p_{\perp,i}}$$





Includes stat. & syst.

linear



linear

$$\tau_{\perp,g} \equiv 1 - T_{\perp,g}$$

spherical

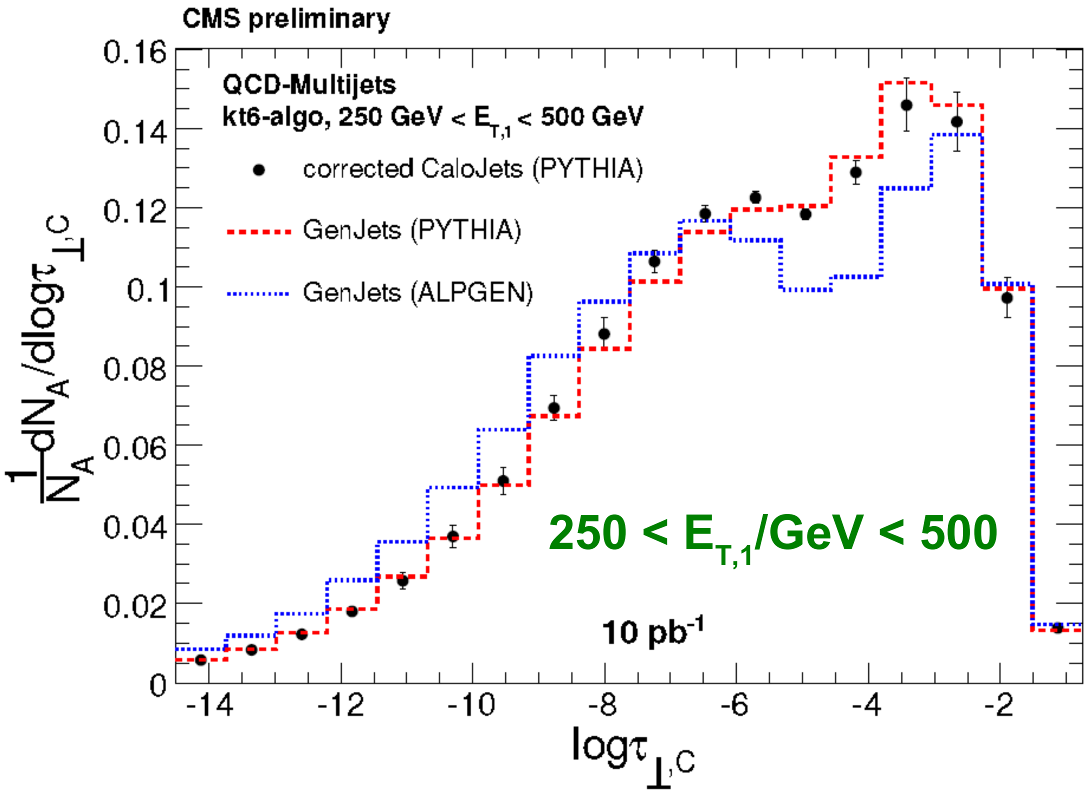
Similar as Event Shapes in e^+e^- and ep

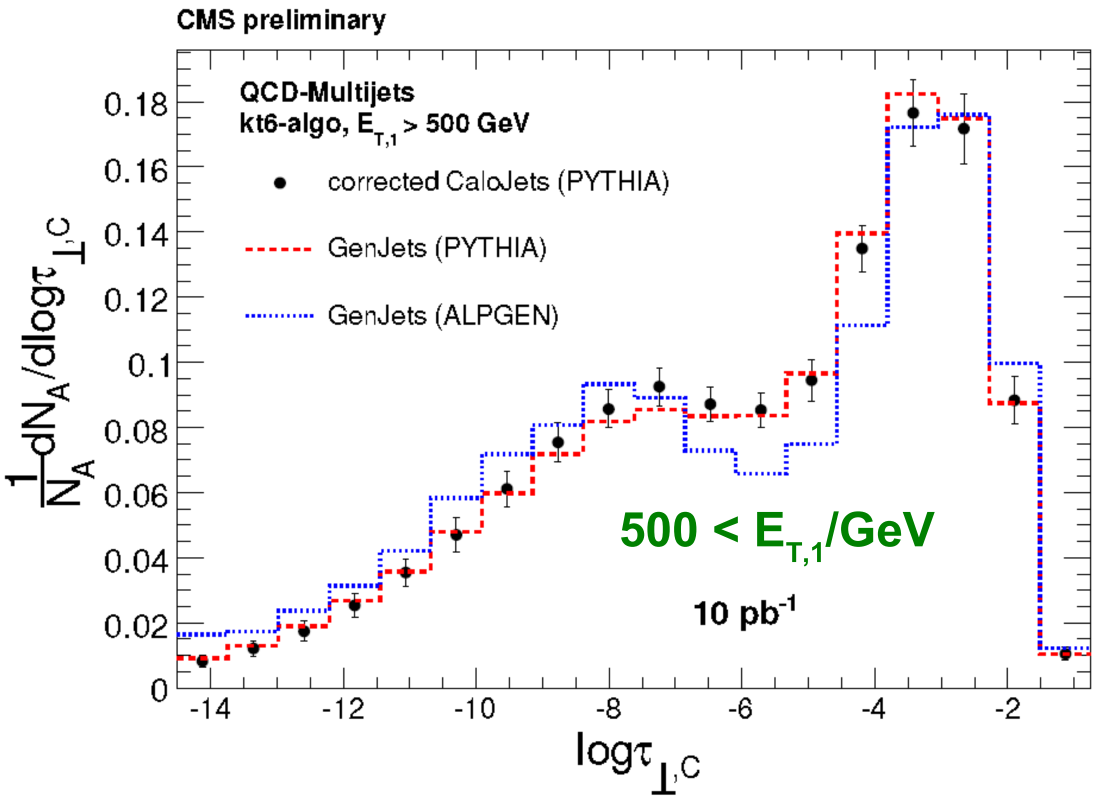
- **In praxis, need to restrict rapidity range:**
$|\eta| < 1.3$ → Transverse central Thrust
- **Less sensitive to JES & JER uncertainty**
- **No luminosity uncertainty**
- **Useful for MC tuning**

CMS PAS QCD-08-003

Event Shapes

- Distributions get more peaked at higher E_T
- Corrected pseudo-data follow behaviour of original Pythia MC
- Alpgen makes different predictions

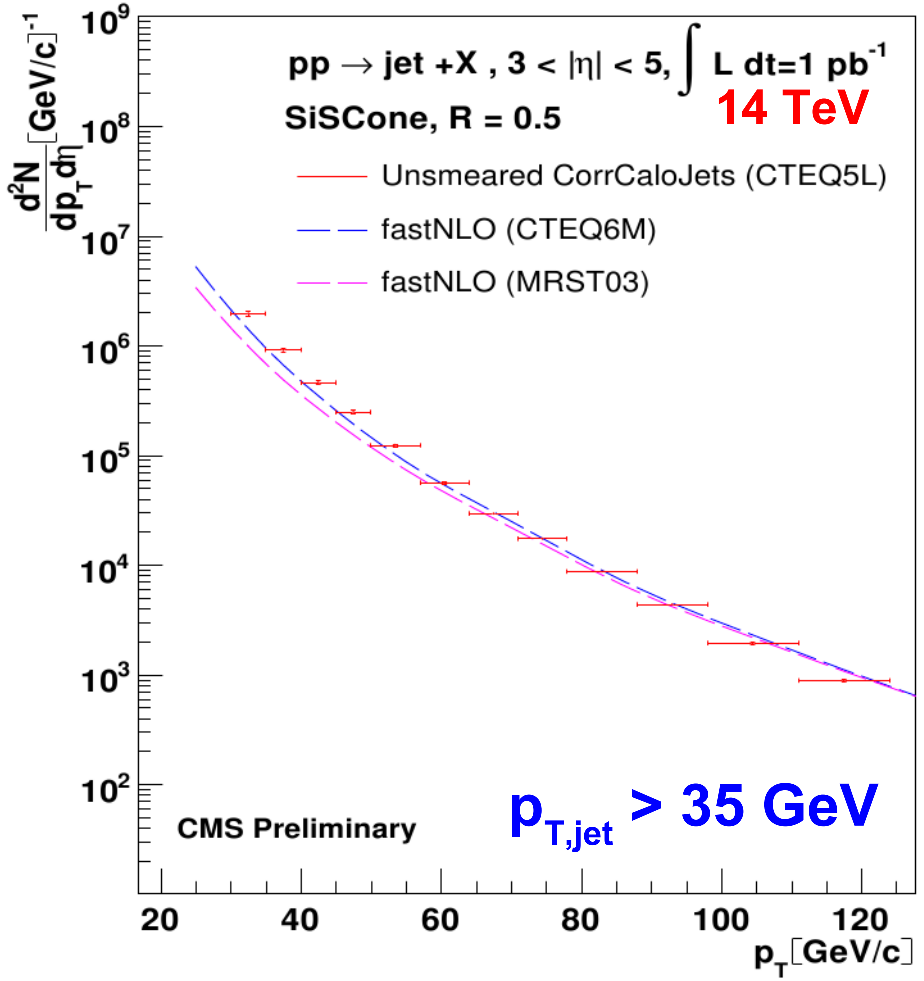




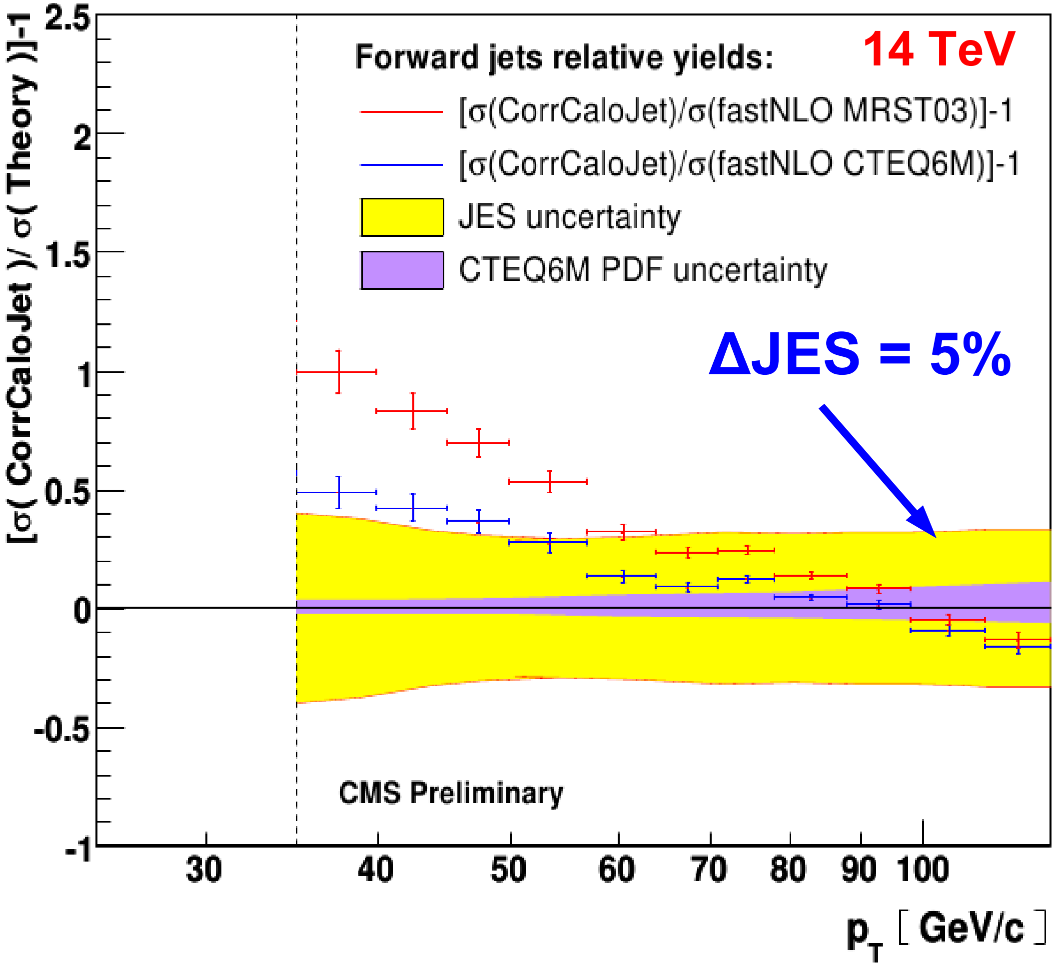
CMS PAS QCD-08-003

Forward Jets and PDFs

Possible constraint on PDFs, but need to know JES!



$p_{T,jet} > 35$ GeV



ΔJES = 5%

CMS PAS FWD-08-001

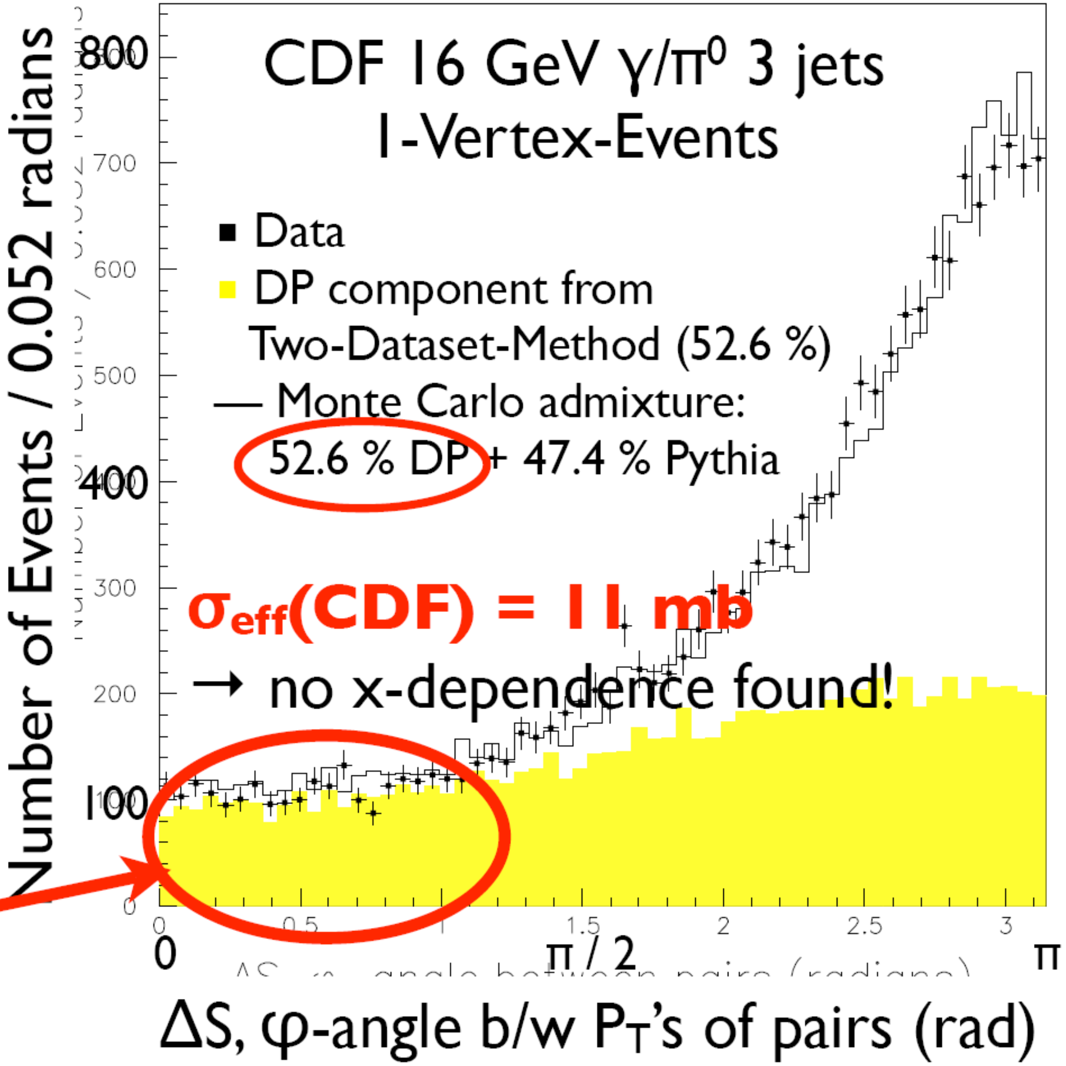
Multiple Parton Interactions

Phase space:

As low as possible in pT:
- photon pT > 10 GeV
- jet pT > 20 GeV for calojets
=> could consider jets from tracks

Double-parton-scattering
- four-jet production (→ AFS, UA2, CDF)
- like-sign W production
- **γ + 3-jet production (→ CDF)**

Need double-parton component to describe the data



σ_{eff}(CDF) = 11 mb
→ no x-dependence found!

Non-perturbative Corrections

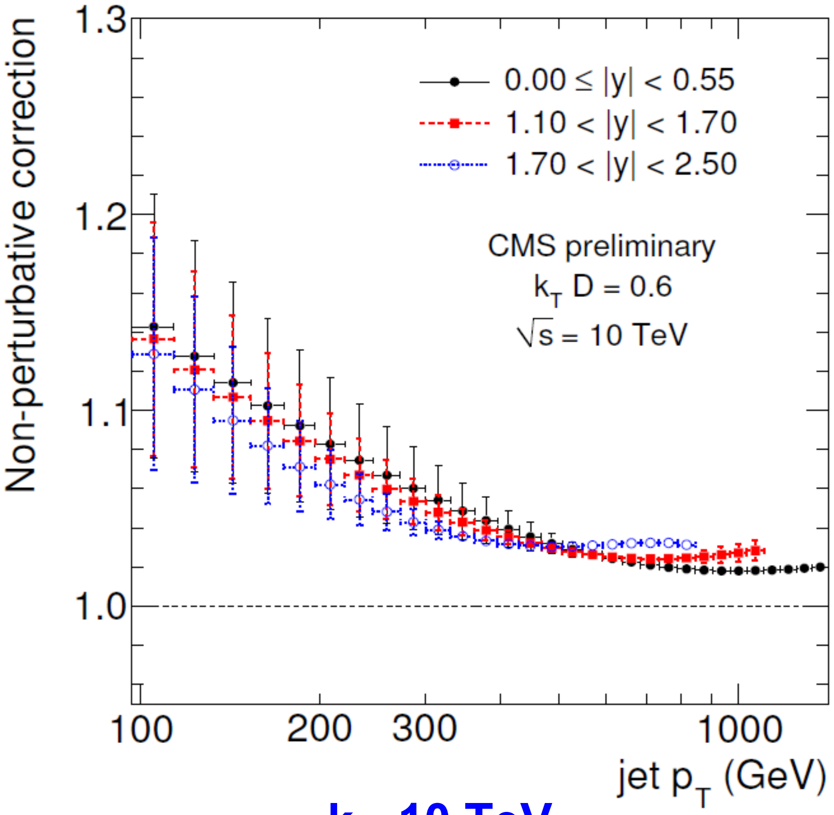
To compare with data correct NLO for:

- Multiple Parton Interactions (MPI)
- Hadronization & Decays (Lund, Cluster)

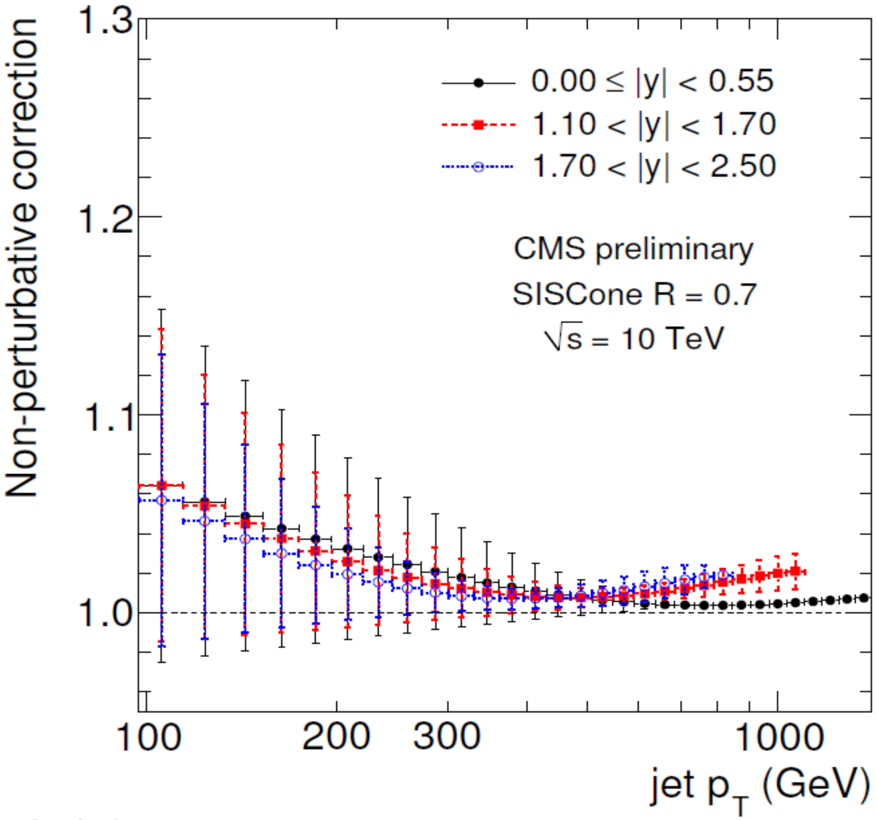
Compared different tuned MC:

- Pythia Tune D6T
- Herwig++

Take correction as average and half the spread as uncertainty.



k_T, 10 TeV



SISCone, 10 TeV

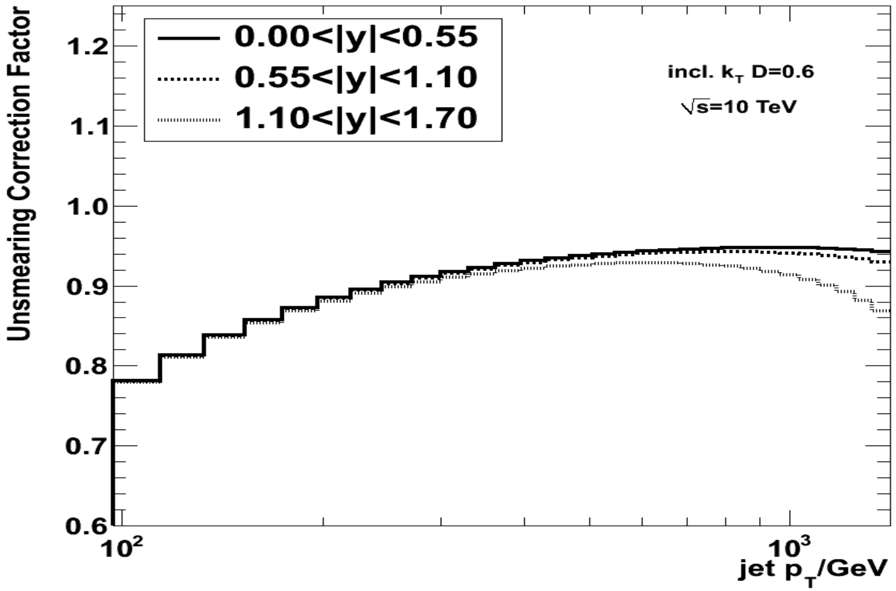
CMS PAS QCD-08-001C

Unsmearing Steps

Motivation

The **observed** cross section is **higher** than the true one due to the falling shape of the spectrum and the finite p_T resolution.

More events migrate into a bin of measured p_T than out of it.



Unsmearing steps:

Analytical expression of the p_T resolution ➡

$$R(p'_T, p_T) = \frac{1}{\sqrt{2\pi}\sigma(p'_T)} \exp\left[-\frac{(p'_T - p_T)^2}{2\sigma^2(p'_T)}\right]$$

Ansatz function with free parameters to be determined by the data ➡

$$f(p_T) = N \cdot p_T^{-a} \cdot \left(1 - \frac{2\cosh(y_{min})p_T}{\sqrt{s}}\right)^b \exp(-\gamma p_T)$$

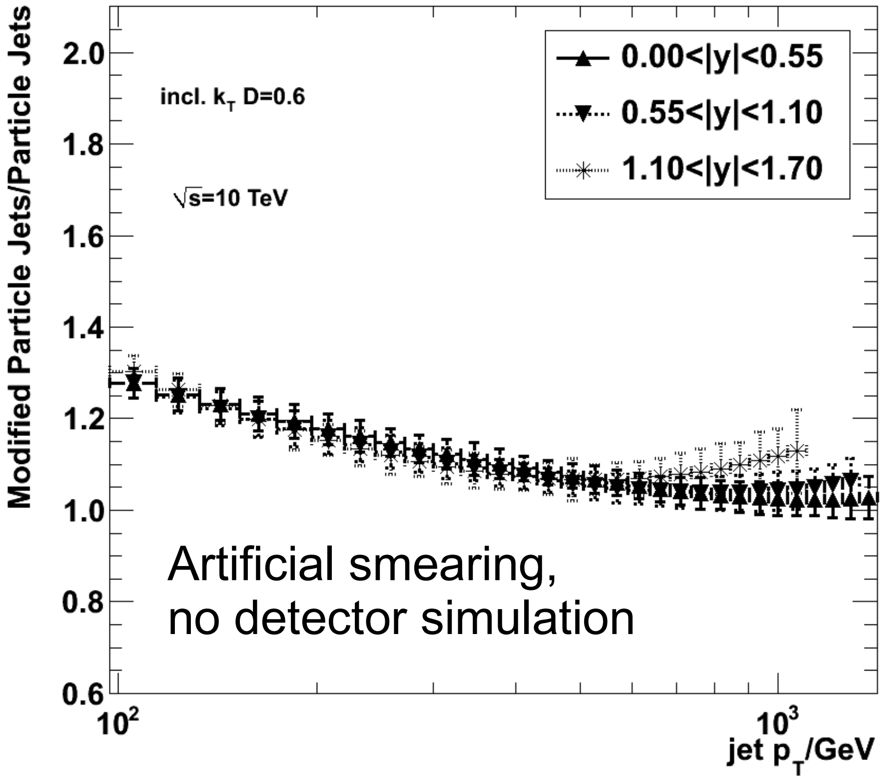
Fitting the data with the Ansatz function smeared with p_T resolution. ➡

$$F(p_T) = \int_0^\infty f(p'_T) R(p'_T, p_T) dp'_T$$

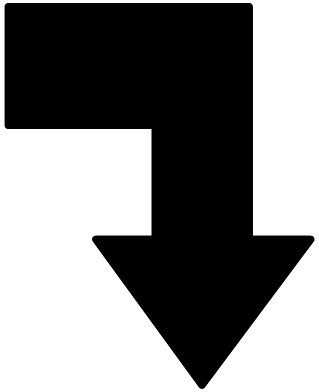
Unsmearing correction calculated bin by bin. ➡

$$C_{bin} = \frac{\int_{bin} f(p_T) dp_T}{\int_{bin} F(p_T) dp_T}$$

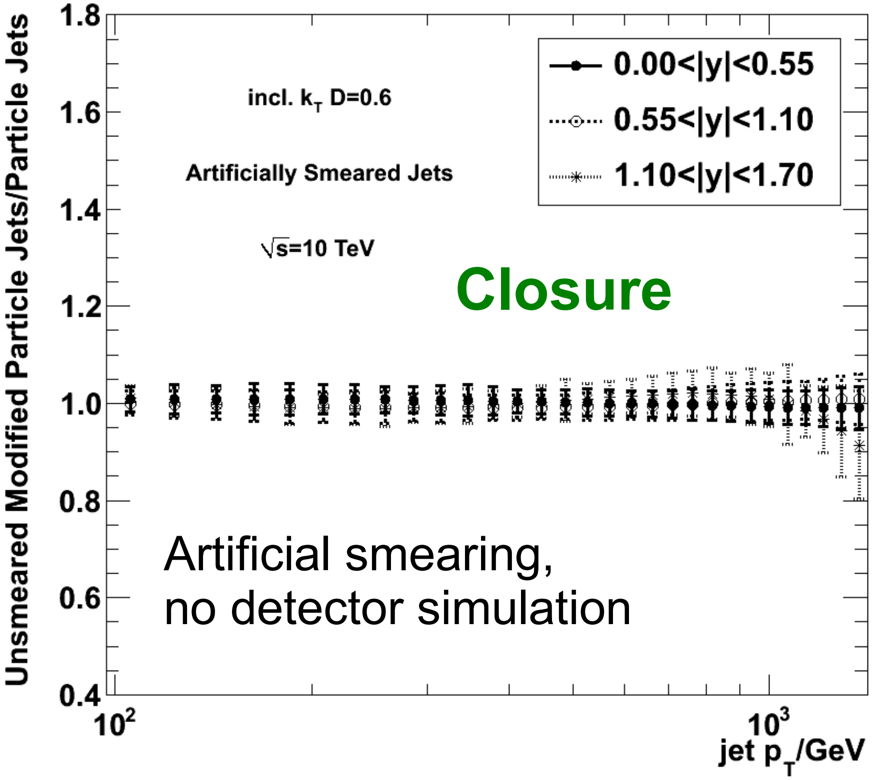
Unsmearing Applied



Artificial smearing,
no detector simulation



Unsmearing by
"Ansatz Method"



Closure

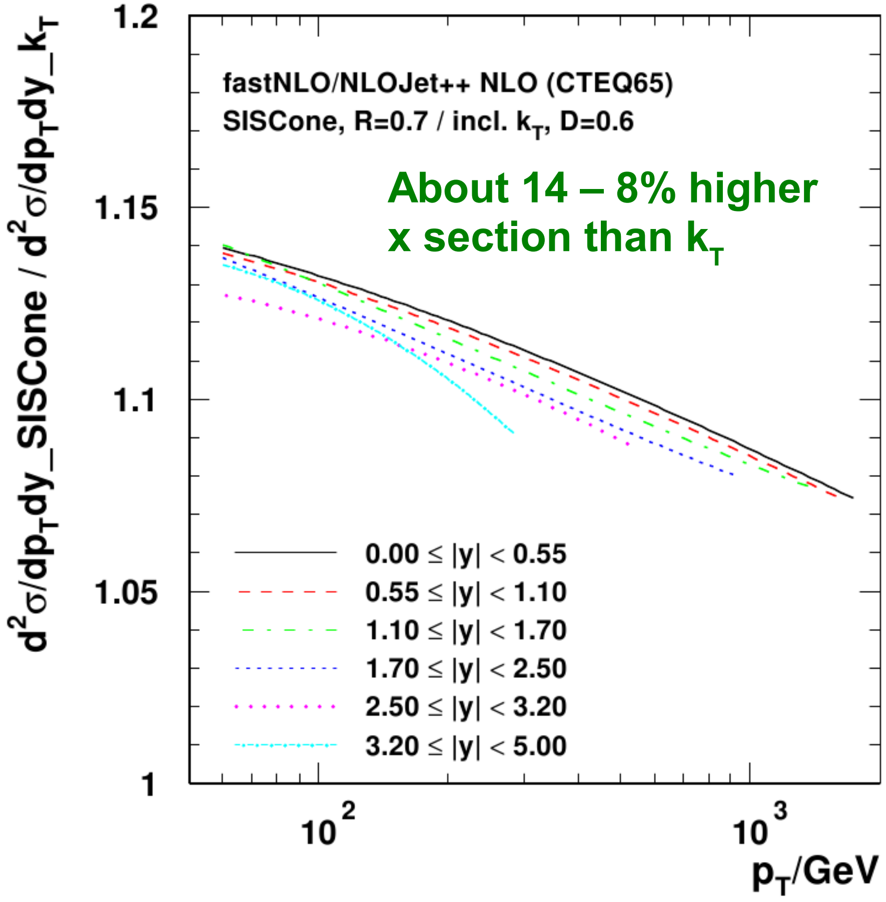
Artificial smearing,
no detector simulation

- Artificially smear jets by Gaussian with an arbitrary but reasonable p_T dependent width.
- Apply ansatz method
- Method corrects p_T smearing effects on steeply falling spectrum

Cross Section Ratios

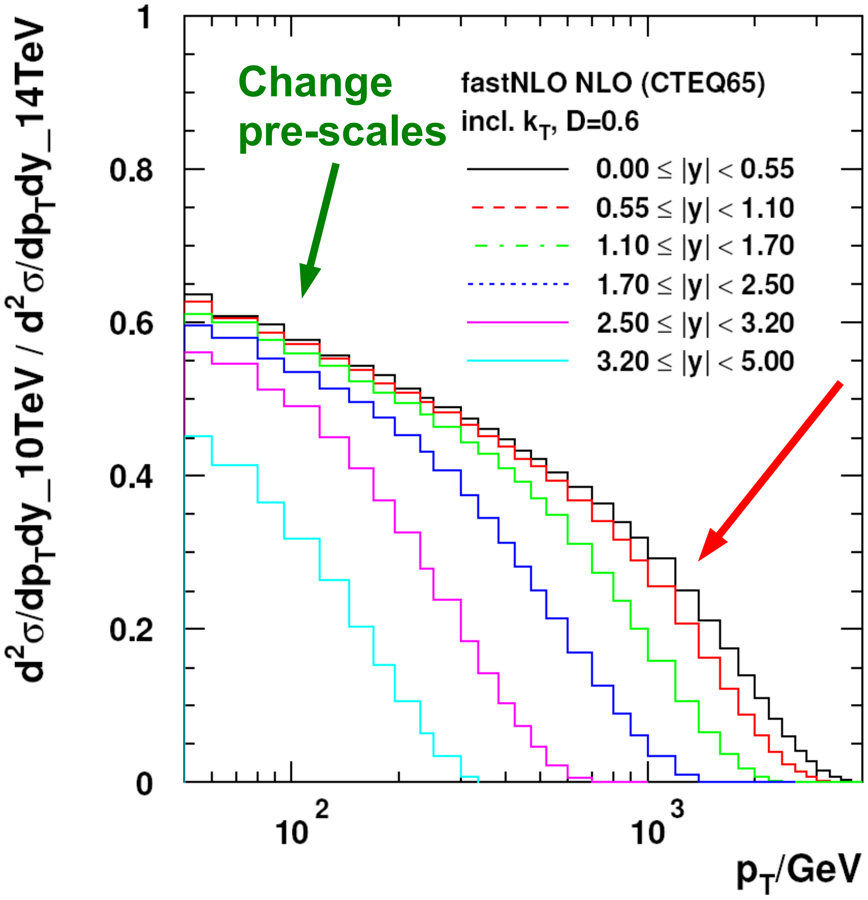
Cross section ratios in 6 bins in rapidity y

SISCone 0.7 / k_T 0.6 @ 10 TeV



About 14 – 8% higher x section than k_T

k_T 0.6 10 TeV / 14 TeV



Change pre-scales

Loss in p_T reach

Partonic Subprocesses

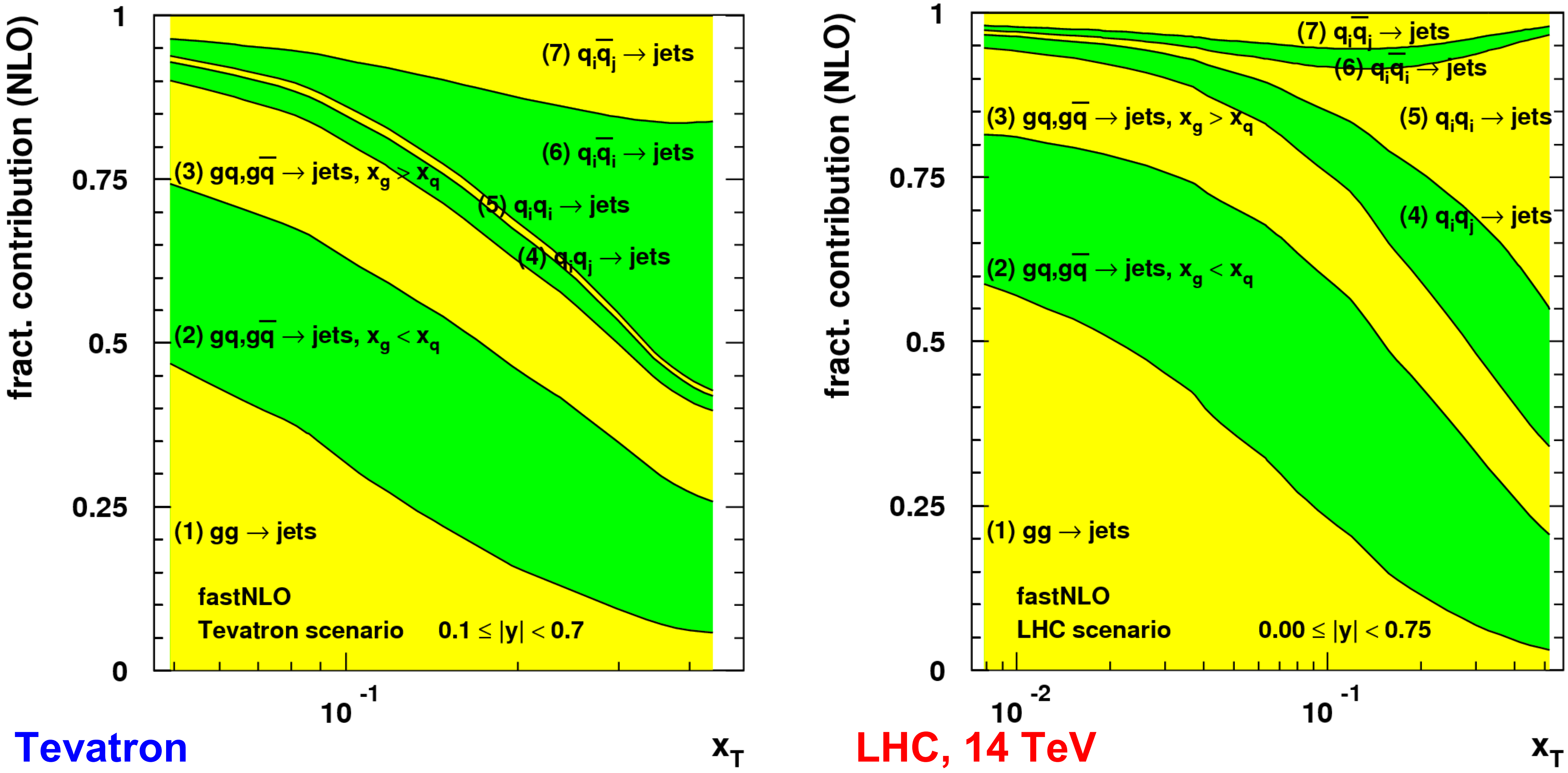
- For hh → jets there are **seven** relevant partonic subprocesses:

$$\begin{array}{lrcll}
1) & gg & \Rightarrow & \text{jets} & \propto H_1(x_1, x_2) \\
2) & qg, \bar{q}g & \Rightarrow & \text{jets} & \propto H_2(x_1, x_2) \\
3) & gq, g\bar{q} & \Rightarrow & \text{jets} & \propto H_3(x_1, x_2) \\
4) & q_i q_j, \bar{q}_i \bar{q}_j & \Rightarrow & \text{jets} & \propto H_4(x_1, x_2) \\
5) & q_i q_i, \bar{q}_i \bar{q}_i & \Rightarrow & \text{jets} & \propto H_5(x_1, x_2) \\
6) & q_i \bar{q}_i, \bar{q}_i q_i & \Rightarrow & \text{jets} & \propto H_6(x_1, x_2) \\
7) & q_i \bar{q}_j, \bar{q}_i q_j & \Rightarrow & \text{jets} & \propto H_7(x_1, x_2)
\end{array}$$

- Seven linear combinations H_i of PDFs

Subprocess Decomposition

Decomposition of the total ppbar, pp → jets cross section (NLO) into subprocesses
At central rapiditySubprozesse against the scaling variable $x_T = 2p_T/\sqrt{s}$



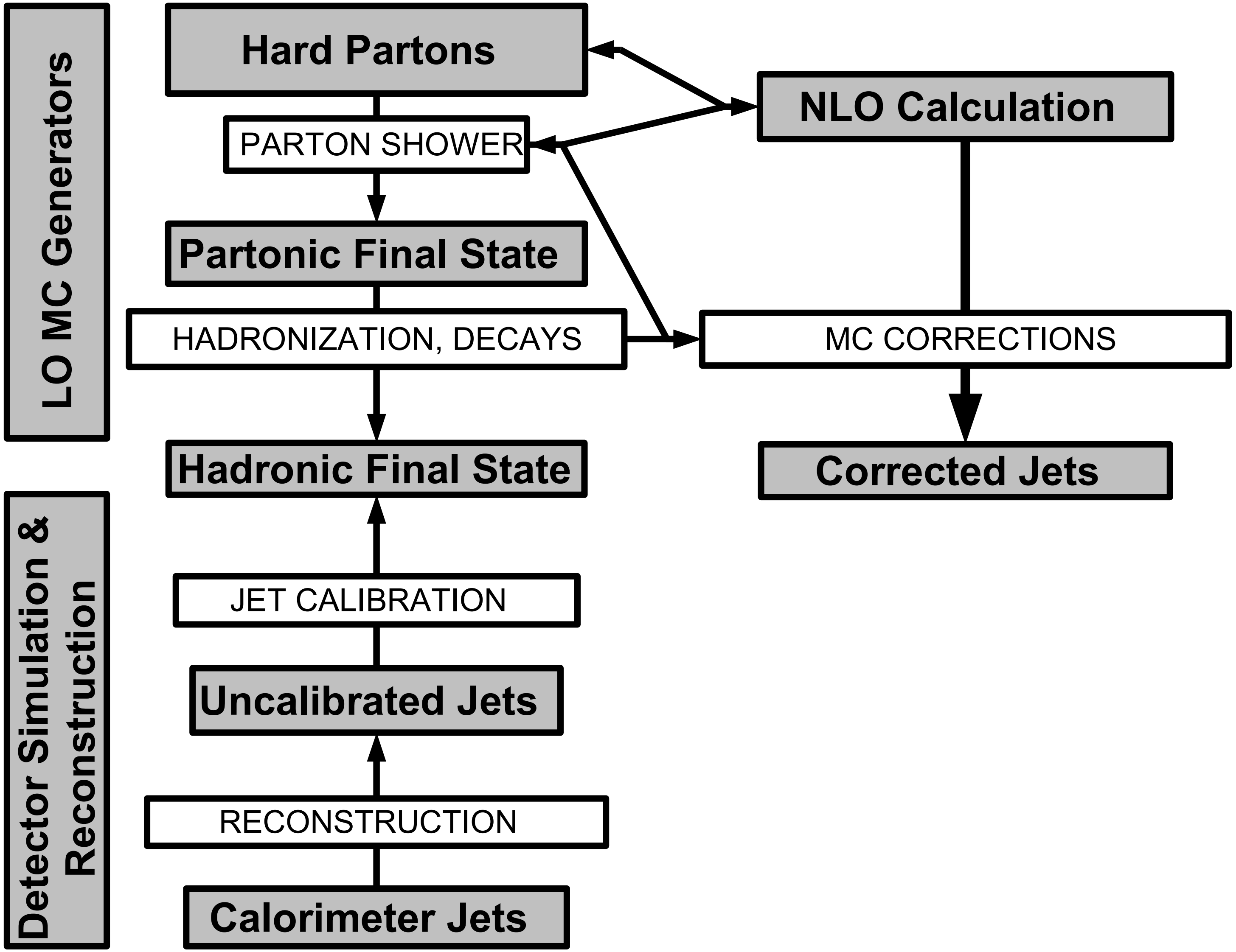
Tevatron

LHC, 14 TeV

Generic Jet Analysis

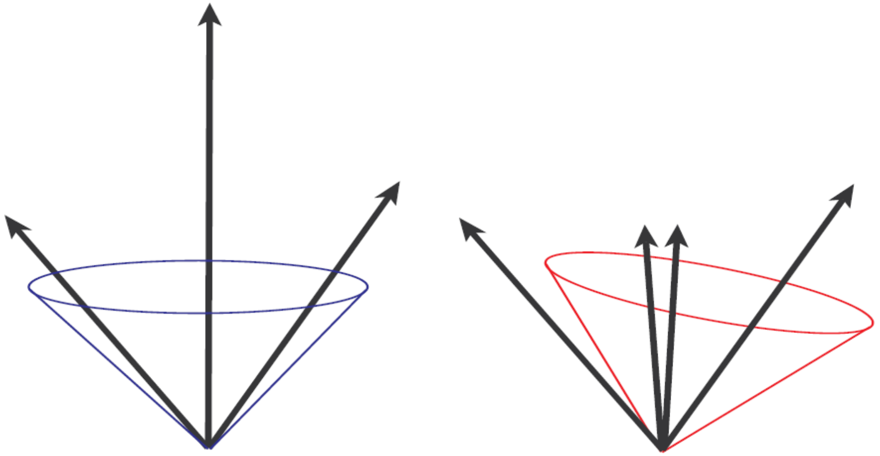
- Requires:
  - PDFs
  - LO & NLO MC
  - Det. simulation
  - Jet energy scale and resolution
  - Calorimeter calibration
  - Jet triggers
  - Luminosity
  - and ...

  Data, of course!



Jet Algorithms

- **Jet Algorithm Desiderata (Theory):**
  - **Infrared safety**
  - **Collinear safety**
  - **Longitudinal boost invariance**
  - **Boundary stability**
  - **Order independence**
  - **Ease of implementation**



Coll. unsafe: Sensitive to the E_T ordering of 4-vectors

Tevatron Run II Jet Physics, hep-ex/0005012