Forward Jet Studies at CMS

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On behalf of the CMS Collaboration

Overview

1. Physics motivation:

(1) Constrain low-x gluon density via forward jets: $d\sigma/dp_T$ in $(3<|\eta|<5)$

(2) Study low-x QCD (parton density evolution) via forward-backward (Mueller-Navelet) dijets: cross-sections, azimuthal distributions, ..

2. Jet reconstruction performance in Hadron-Forward calorimeter:

- Jet resolutions: p_T, eta, phi
- Jet↔Parton: Matching efficiency vs. p_T

3. Results:

(1) Inclusive forward jets $d\sigma_{jets}/dp_T$: sensitivity to PDFs

(full CMS detector simulation and reconstruction)

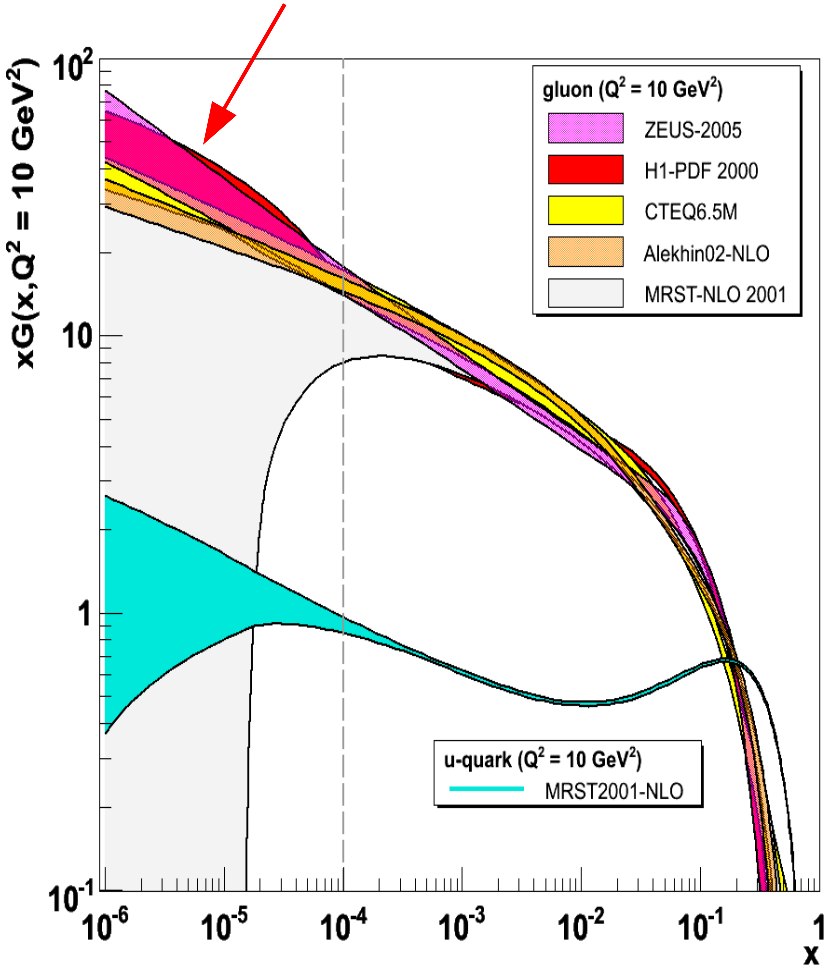
(2) "Mueller-Navelet" dijets: $dN_{MN\text{-}dijet}/dp_T$ vs. $\Delta\eta$, azimuthal decorrelation $dN/d\Delta\phi$, $\langle\cos(\Delta\phi)\rangle$

(PYTHIA/HERWIG (gen.-level) vs. BFKL analytical calculations)

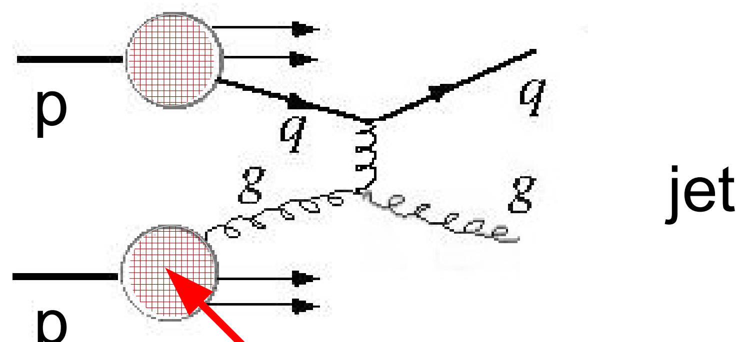
4. Summary & Outlook

Motivation (1): Gluon PDF via fwd. jets

- Low-x gluon density in the proton is poorly known:



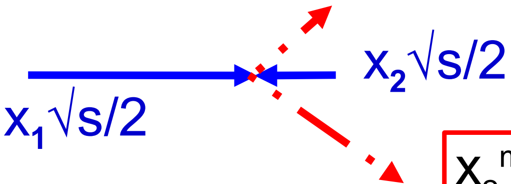
- Jet production constrains PDFs:



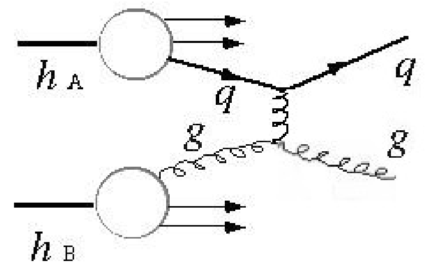
$$d\sigma(pp\rightarrow jet) = PDF(x_1,Q^2) \otimes PDF(x_2,Q^2) \otimes d\sigma(qg\rightarrow jet)$$

Motivation (1): Gluon PDF via fwd. jets

- Forward jet production constrains low-x PDFs:



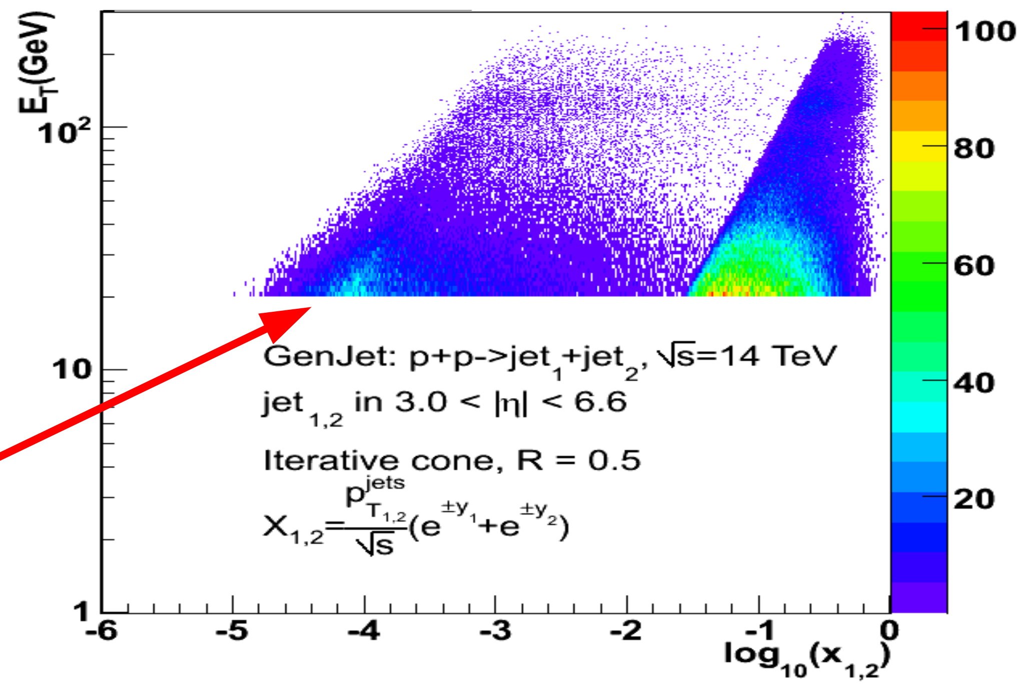
$x_2^{min} \sim p_T/\sqrt{s} \cdot e^{-y} = x_T \cdot e^{-y}$



Every 2-units of y,
x^{min} decreases by ~10

- Forward jet production in CMS fwd. calorimeters:

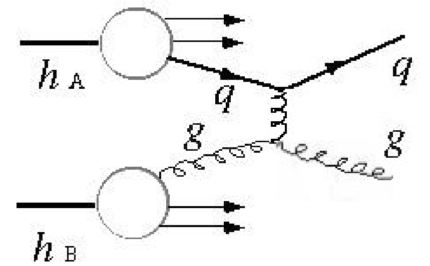
Jets in HF (3.<|η|< 5.)
sensitive to : **$x \sim 10^{-4}$**
Jets in CASTOR
(5.1<|η|< 6.6): **$x \sim 10^{-5}$**



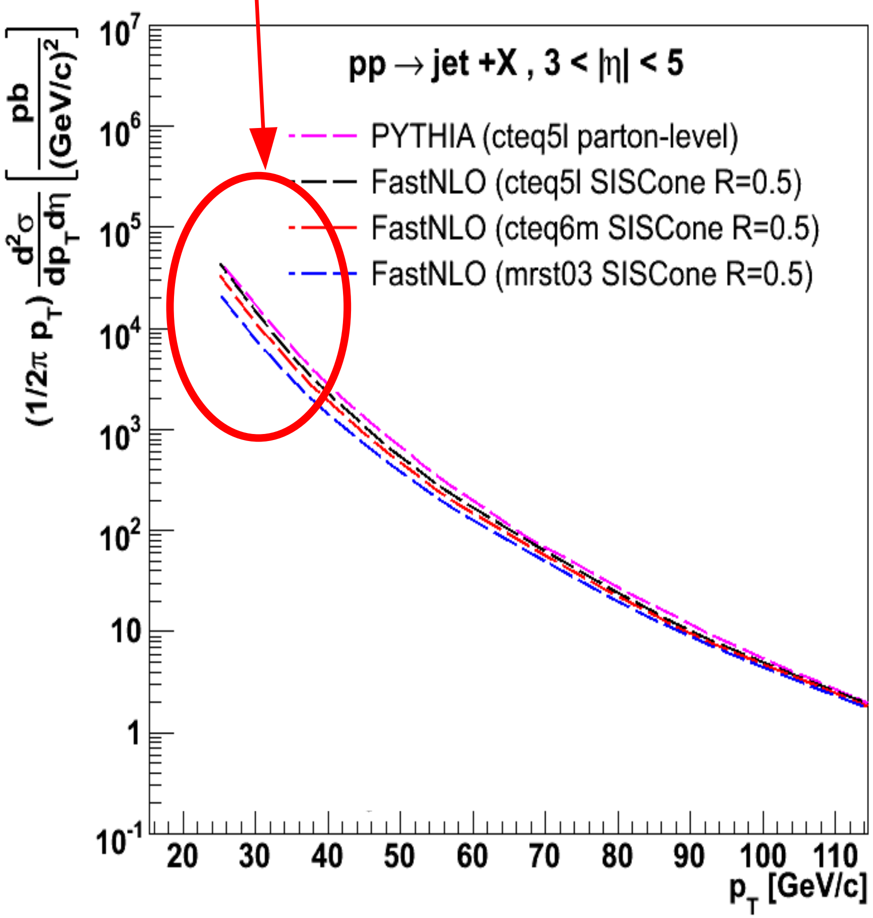
(PYTHIA default PDF: CTEQ5L)

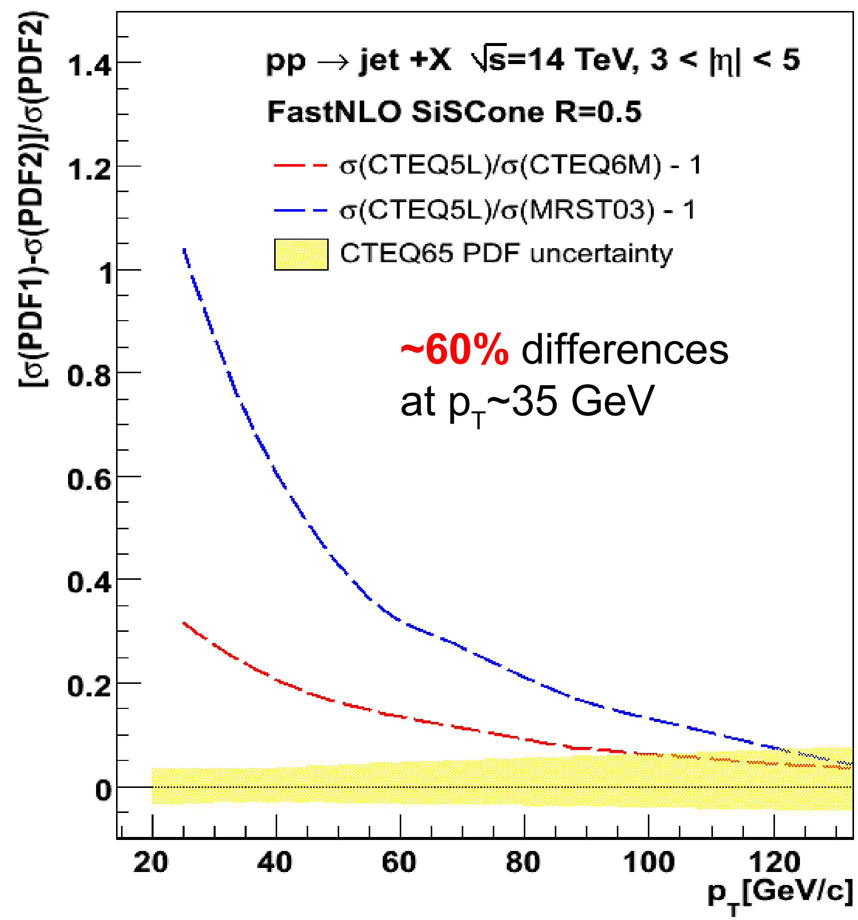
Motivation (1): Gluon PDF via fwd. jets

- Forward jet (3.<|η|< 5.) spectrum: sensitivity to different PDF parametrizations:



(generator-level)





Motivation (2): Low-x QCD via forward-backward dijets

- Mueller-Navelet dijets with large y separation very sensitive to low-x QCD evolution (testing ground for BFKL):

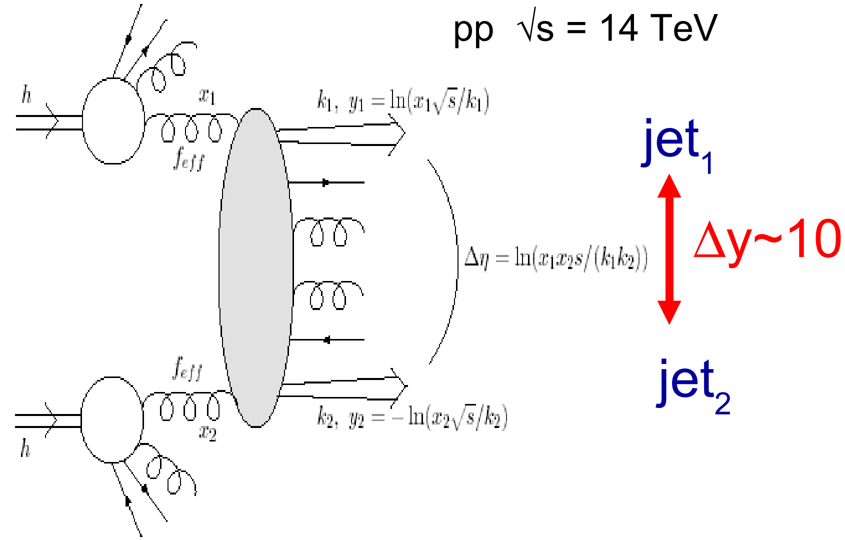
BFKL: extra radiation between the 2 jets will smear out back-to-back topology

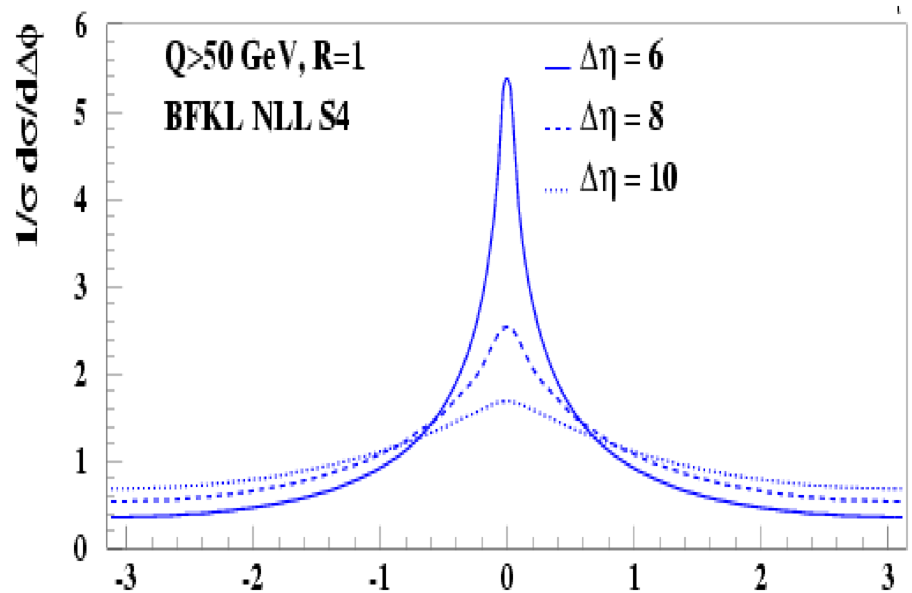
A.H.Mueller, H.Navelet, NPB282 (1987)727

(enhanced radiation partially compensated by gluon saturation ?)

- Increased azimuthal decorrelation with increasing Δy (w.r.t. DGLAP collinear-factorization):

pp $\sqrt{s}$ = 14 TeV





[A.Sabio-Vera, F.Schwennsen]
[C.Marquet, Royon]

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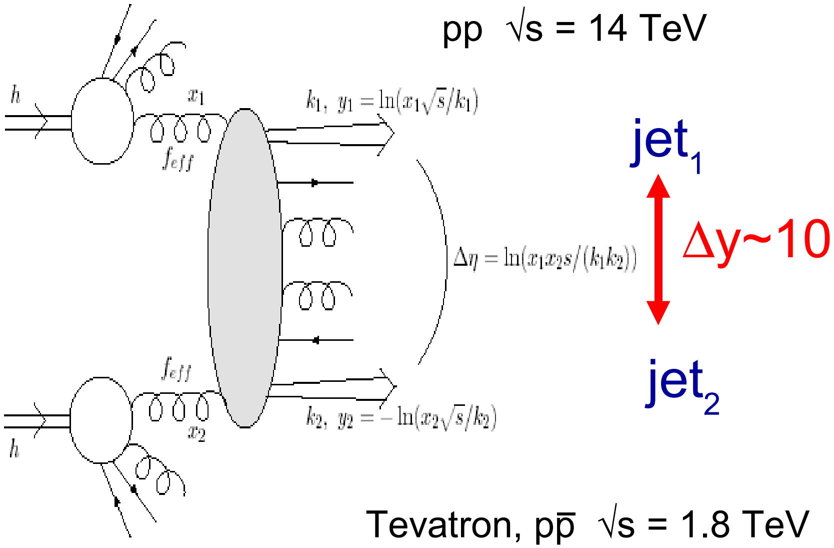

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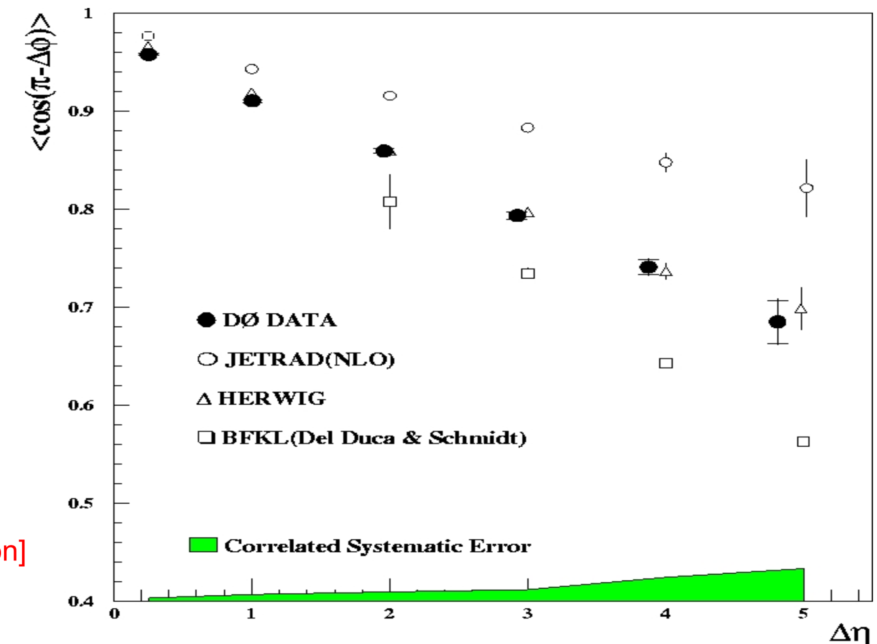
- Increased azimuthal decorrelation with increasing Δy (w.r.t. DGLAP collinear-factorization):

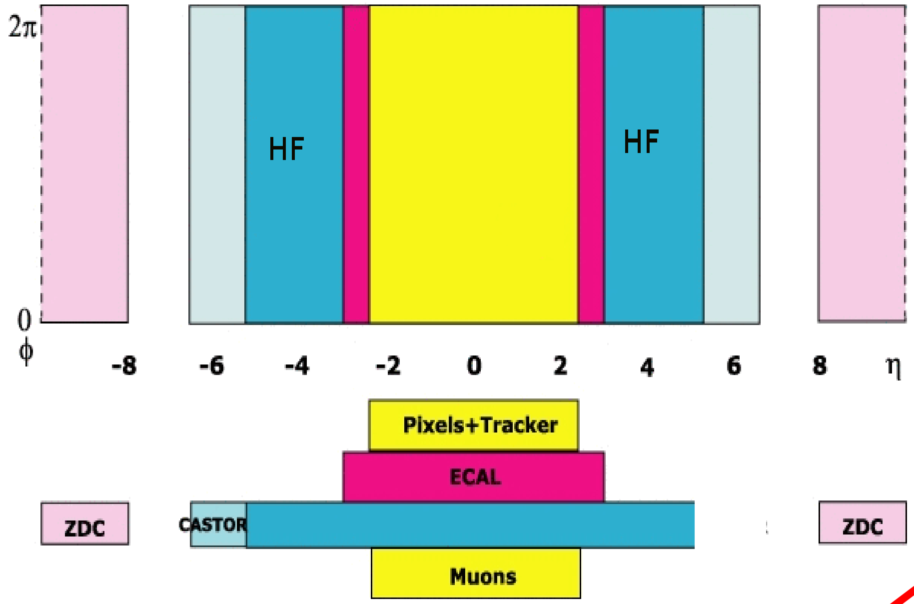
Tevatron, $p\bar{p}$ $\sqrt{s}$ = 1.8 TeV

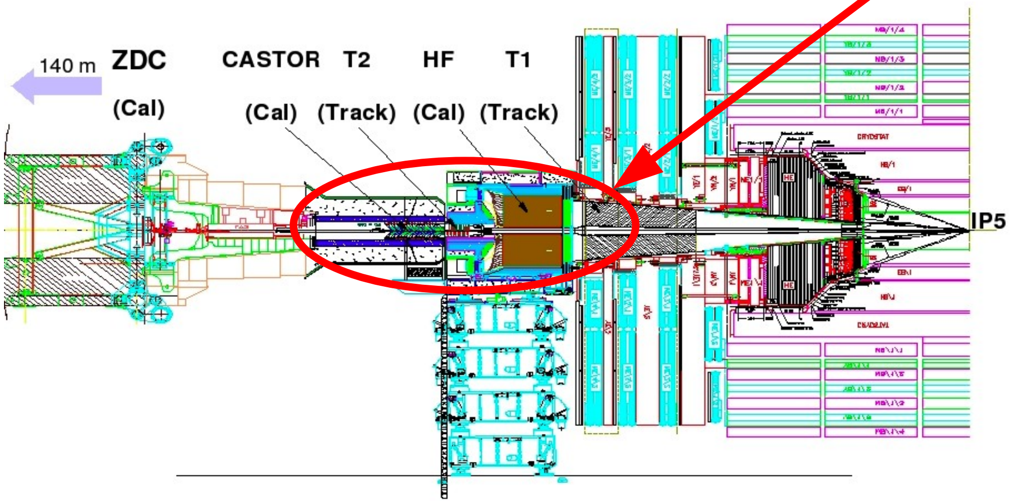


S. Abachi et al. [DO Collaboration]
Phys. Rev. Lett. 77, 595 (1996).

2. Forward jet reconstruction (CMS performance)

CMS forward calorimeters





H(adron)F(orward):

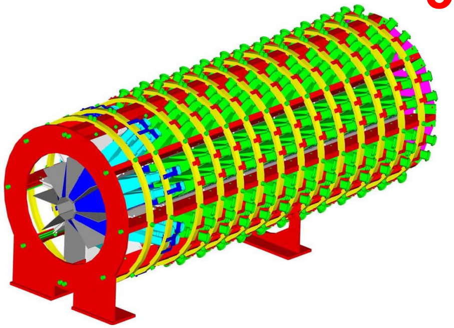
$3<|\eta|<5$

Granularity: $\Delta\eta\times\Delta\phi \sim 0.175\times 0.175$

CASTOR:

azimuthally symmetric EM/HAD calorimeter

$-5.2>\eta>-6.6$



More in B. Roland's talk

Jet Algorithms in CMS

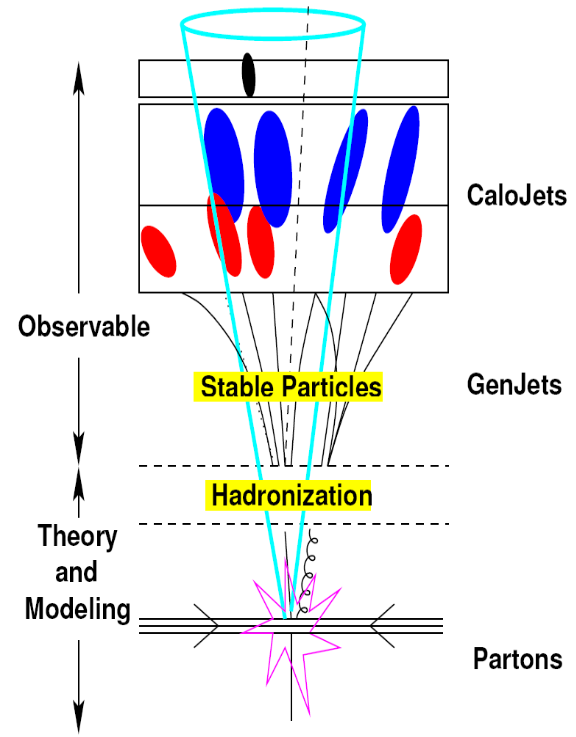
CMS PAS JME-07-003

- 3 jet algorithms used:

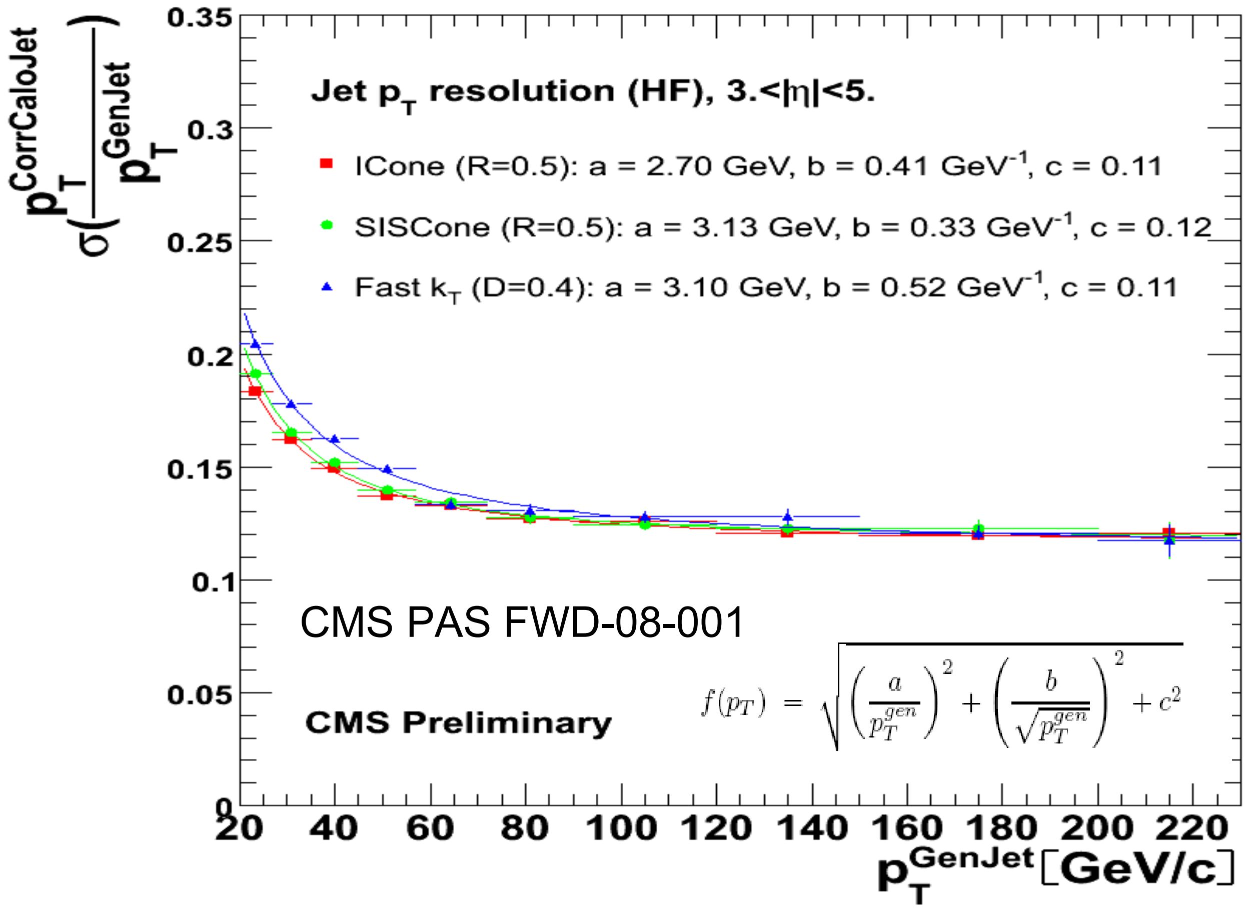
1) Iterative Cone (Icone)
   - Iteratively searches for stable cones
   - Input objects assigned to a jet are removed before the next iteration
   - Seed based, not Infrared Collinear (IRC) Safe
   - Seed ET > 1 GeV

2) SISCone
   - Seedless IRC Safe Cone algorithm
   - Searches for all stable cones of size $R=\sqrt{(\Delta y)^2 + (\Delta\Phi)^2}$
   - No remaining unclustered inputs

3) Fast (kT)
   - Controlled by the jet separation parameter D (determines jet “size”)
   - Uses sequential recombination of 4vectors
   - Based on relative kT
   - Infrared Collinear Safe



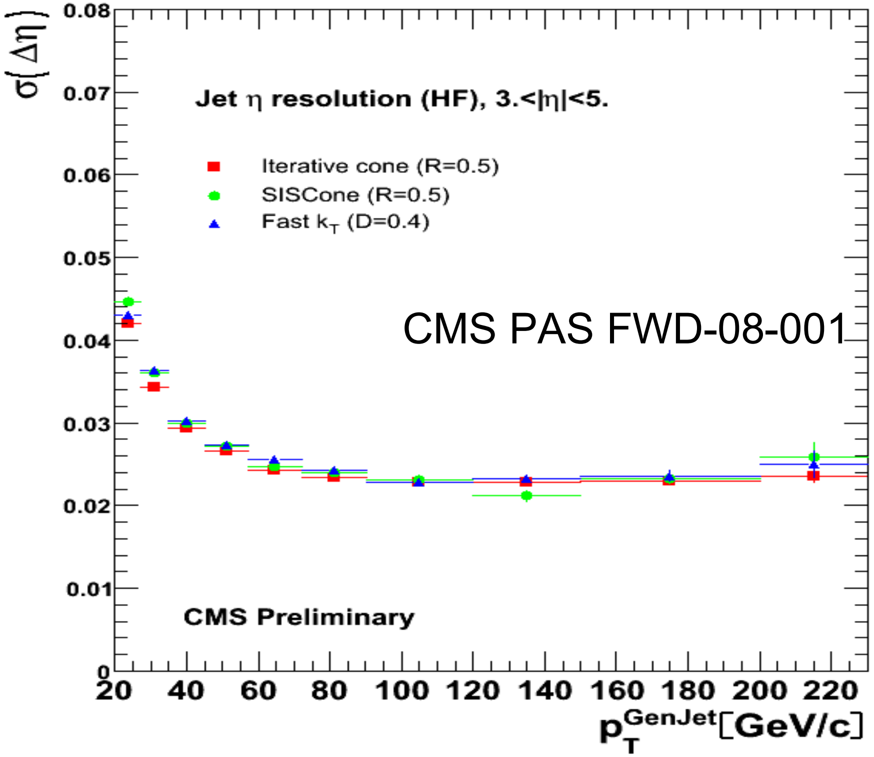
HF (3<|η|<5) jet P_T resolution



- p_T resolution for HF, 3< |η|<5
  ~20% (E_T~20 GeV), ~12% (E_T>100 GeV)
- ICone~Fast k_T~SISCone. (Better resolution than at central rapidities: cosh(η) boost !)

HF($3<|\eta|<5$) position (η,ϕ) resolution

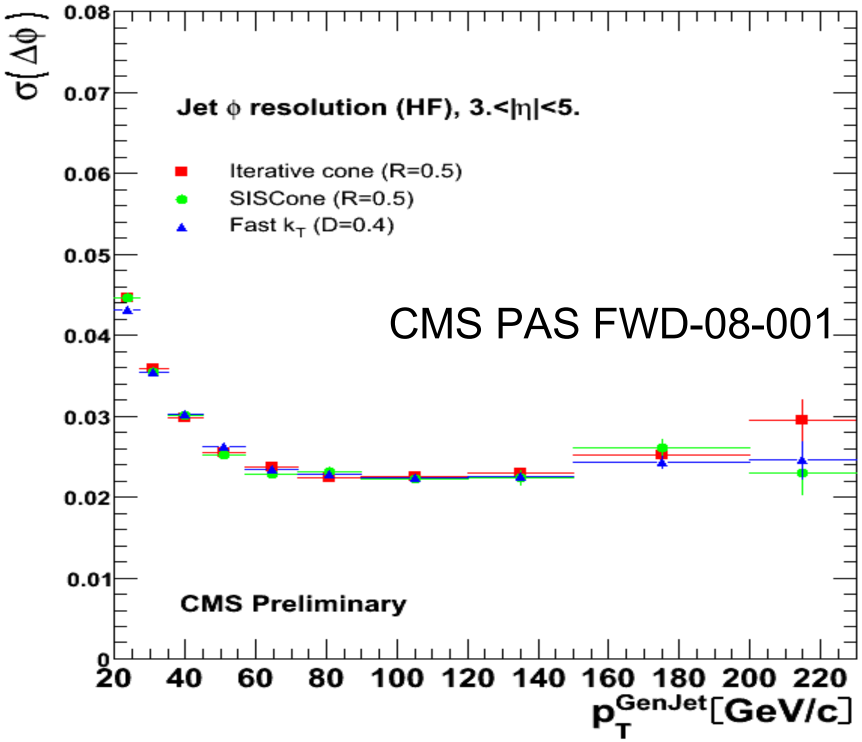
- Good η resolution



~0.05 (p_T~20 GeV)
~0.020 (p_T>100 GeV)

- ICone~Fast k_T~SISCone.

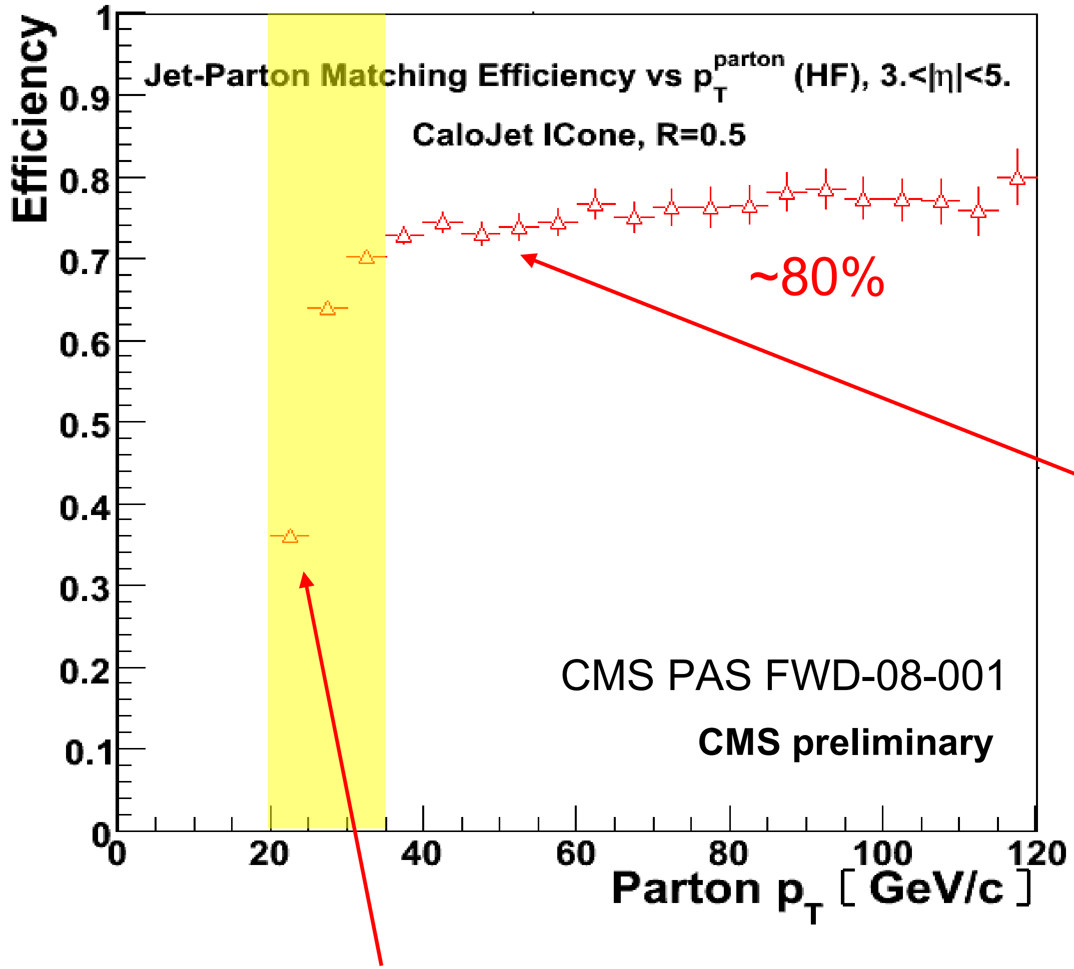
- Good ϕ resolution:



~0.050 rads (p_T~20 GeV),
~0.020 rads (p_T>100 GeV)

- ICone~Fast k_T~SISCone.

Parton – CalorimeterJet matching efficiency



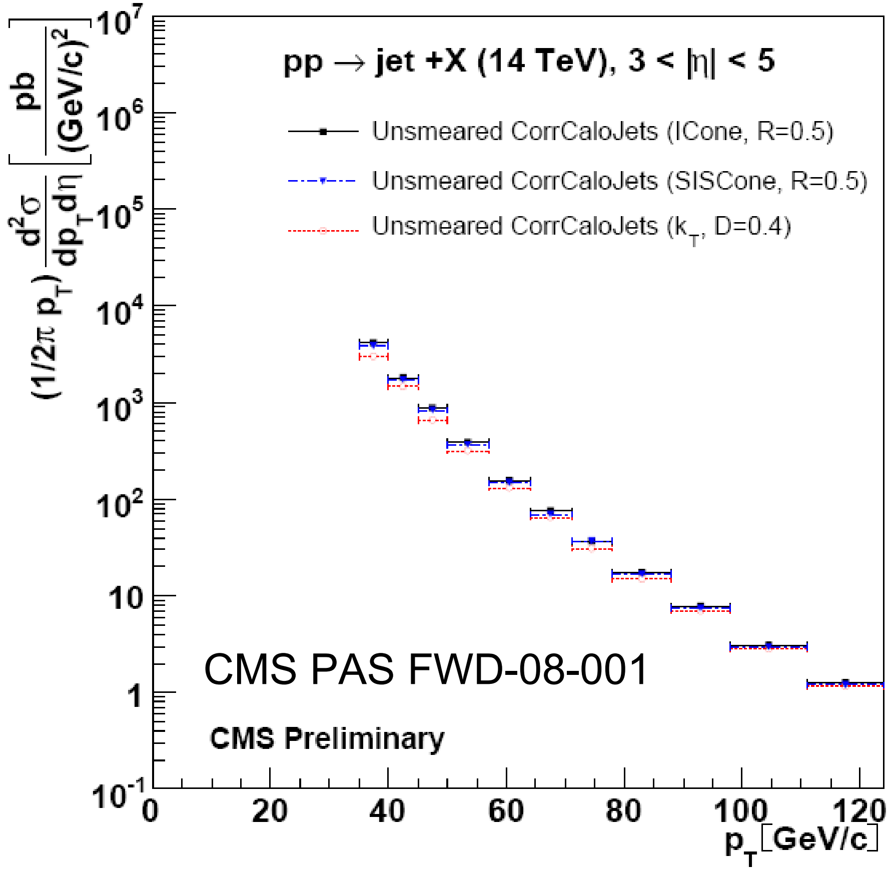
- Good matching for p_T>~35 GeV/c: lowest p_T bin of fwd spectrum considered hereafter

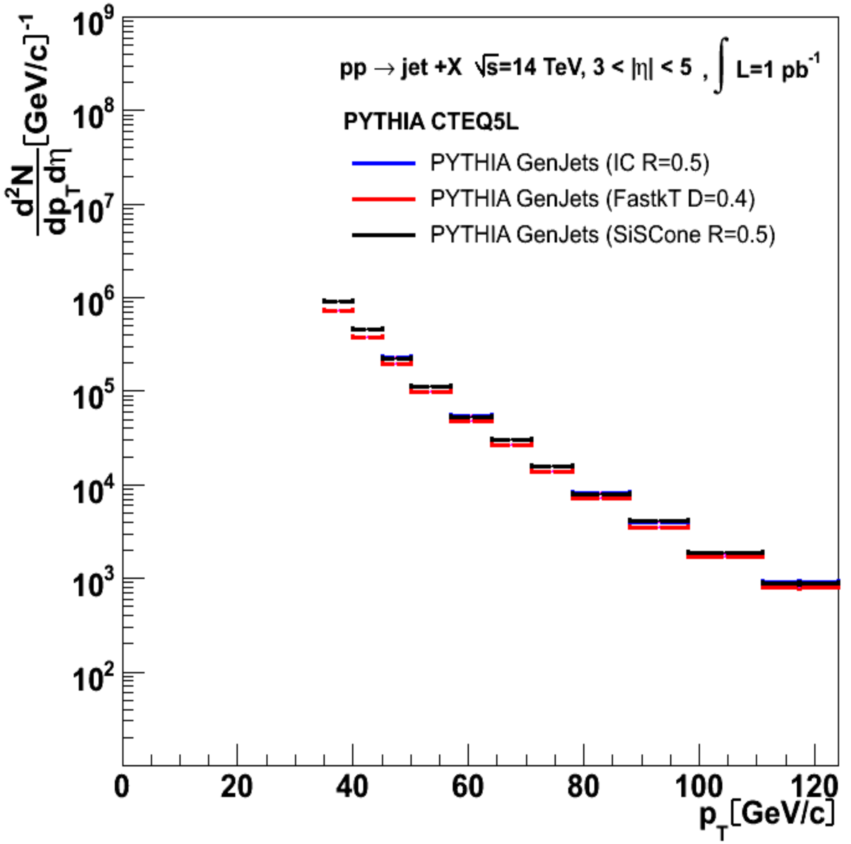
- Most of reco jets at p_T~20 GeV/c not from hard partons (underlying event, beam remnants, ...)

3. Results:
Single forward jet spectrum.
PDF sensitivity
(full CMS detector simulation & reconstruction)

Forward jet spectrum (1 pb^{-1}): different algorithms

- Invariant cross-sections : ICone, SiSCone, Fastk_T
- Yields: ~1M fwd. jets with p_T>35 GeV/c (generator-level)

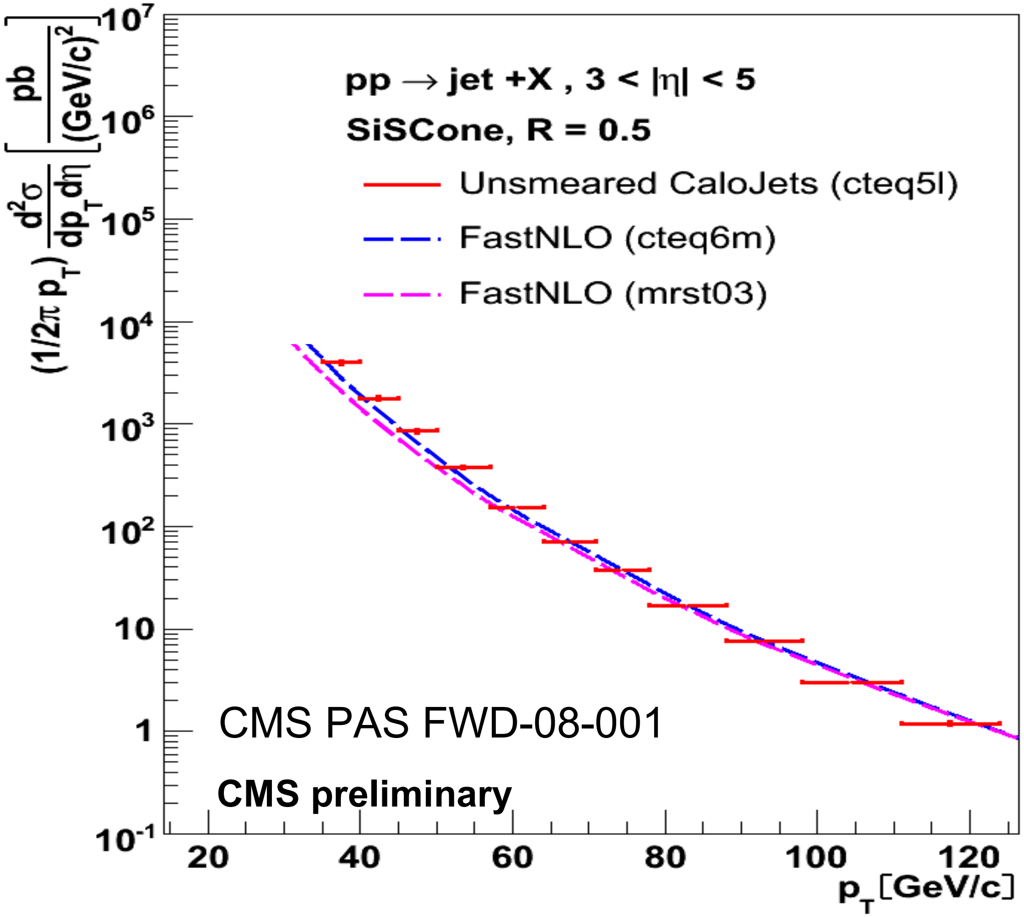




- SISCone & IterativeCone yields are very similar.
- FastkT is 20%-25% lower than cone algorithms below $p_T \approx 80$ GeV/c

Forward jet spectrum (1 pb^{-1}): PDF sensitivity

- Invariant cross-sections: CalorimeterJets vs. NLO-MRST03,CTEQ6M
- Small <u>point-to-point</u> errors: statistical + 2%-5% p_T-resolution unsmearing

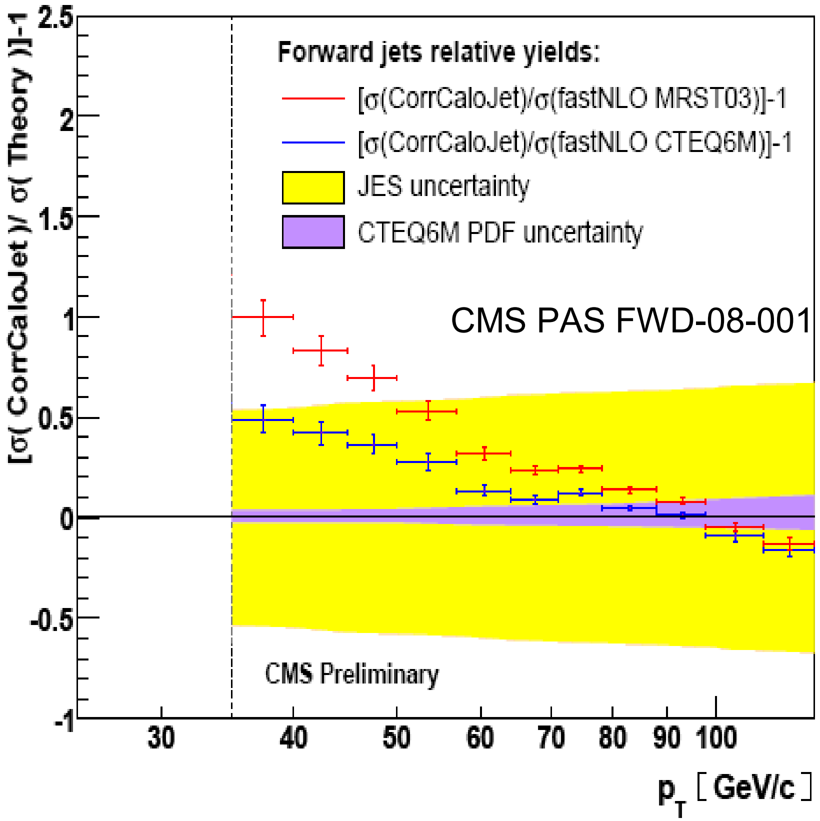


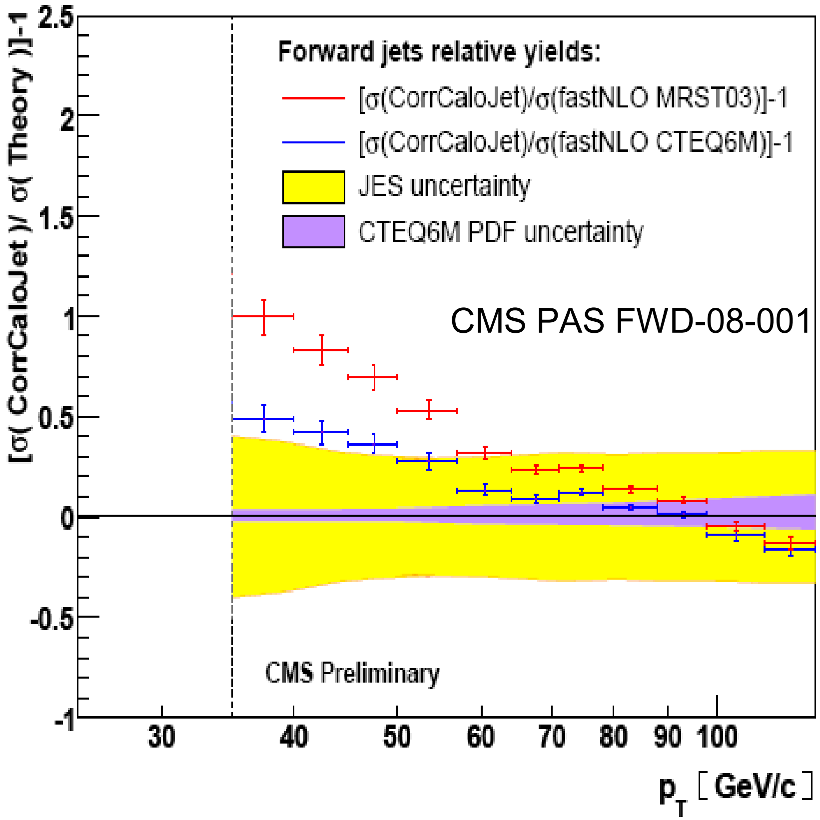
FastNLO: K.Rabbertz et al.
hep-ph/0609285

- Large forward jet statistics available to test different PDFs

Forward jet spectrum (1 pb^{-1}): PDF sensitivity

- Fractional x-section difference: CalorimeterJets (PYTHIA,CTEQ5L) vs. NLO-MRST03, NLO CTEQ6M
- Small p2p errors (stat.+E-resol.) but large p_T-corr Jet-Energy-Scale (JES) errors: ~40-50%

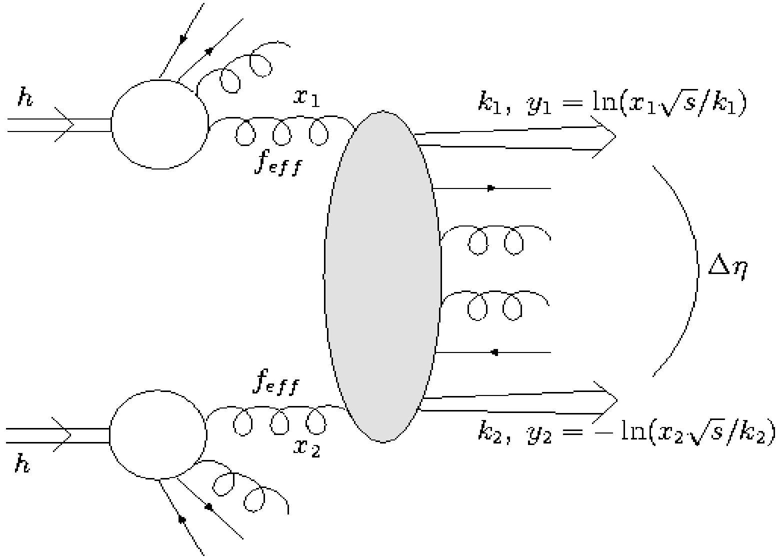


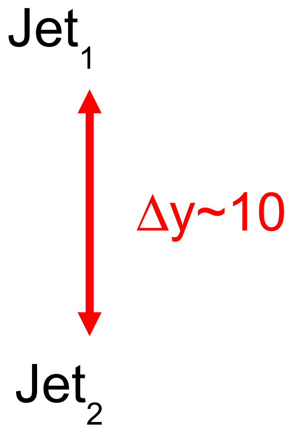


- JES scenario-1 (10%): Small PDF sensitivity <50 GeV/c
- JES scenario-2 (10%-5%): PDF sensitivity <50 GeV/c

4. Results:
”Mueller-Navelet” dijets.
Yields, azimuthal decorrelation
(PYTHIA/HERWIG generator-level)

Mueller-Navelet dijets: kinematic cuts



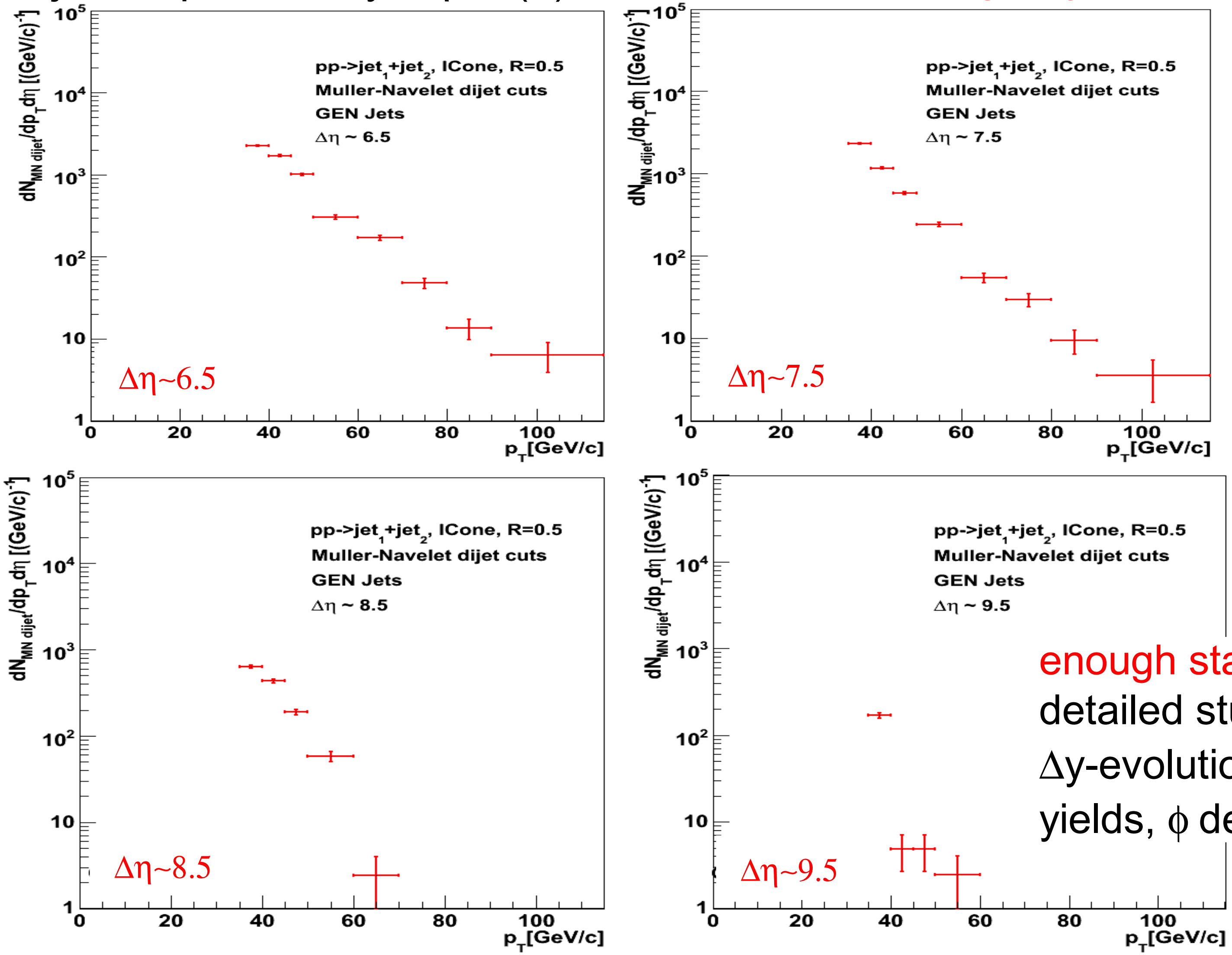


- 2 forward jets : $3. < |\eta| < 5.$
- Moderately hard: $p_T > 35$ GeV (good parton-jet matching)
- Similar energy (minimize DGLAP rad.): $|p_{T1}-p_{T2}| < 5$ GeV
- Jets in opposite: $\eta_1 * \eta_2 < 0.$

Expected MN dijet yields ($3<|\eta|<5$, 1 pb^{-1})

- For $\mathscr{L}$~1 pb^{-1}, we expect: ~5000 (~100) Mueller-Navelet-type dijets separated by $\Delta\eta$~6 (9).

PYTHIA-GENJET

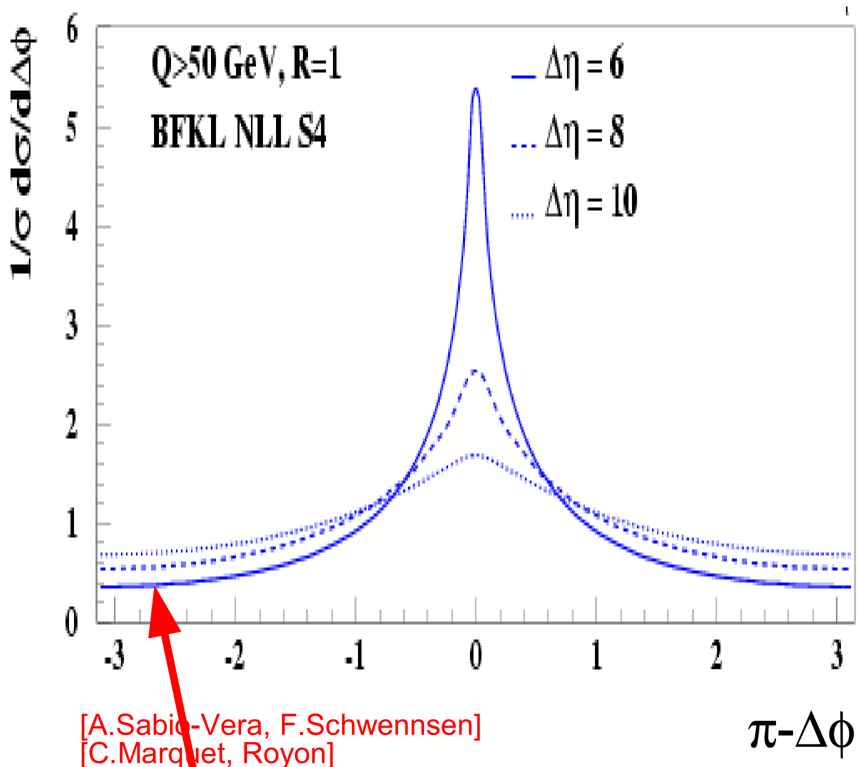


$p_{T\,1,2}$> 35 GeV

enough stats for detailed studies of Δy-evolution for $3<|\eta|<5$: yields, ϕ decorrelation

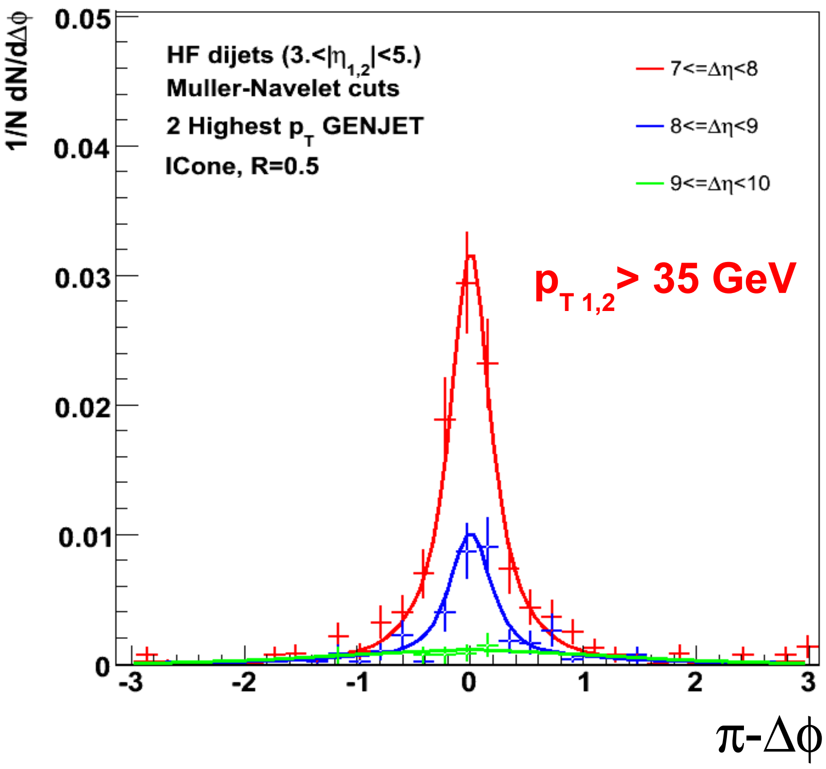
MN dijets: azimuthal decorrelation (GenJet)

BFKL calculations



[A.Sabio-Vera, F.Schwennsen]
[C.Marquet, Royon]

PYTHIA

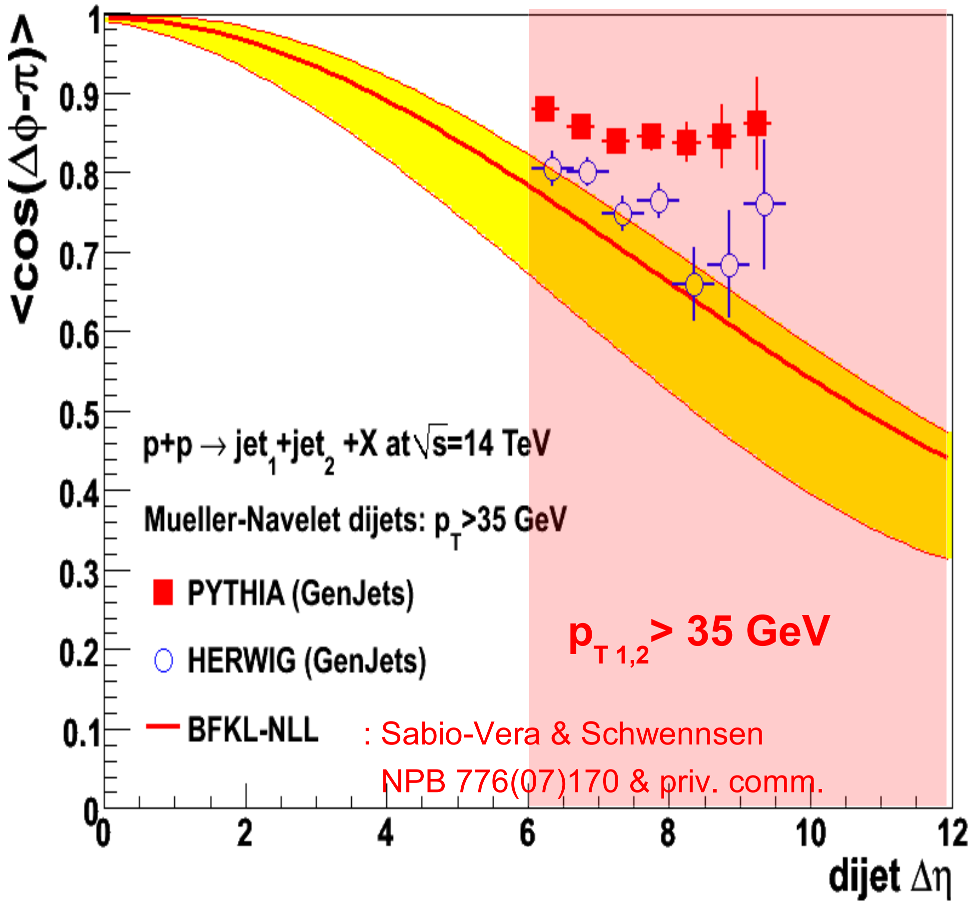


Large azimuthal decorrelation observed with increasing $\Delta\eta$.

Small azimuthal decorrelation observed in GENJET with increasing $\Delta\eta$.

MN dijets: ⟨cos(Δϕ–π)⟩
Pythia-Herwig-BFKL (Gen-Level)

- Average cos(Δϕ–π) vs. Δη:



- HERWIG shows ~15% more decorrelation than PYTHIA and ~20% less than BFKL analytical estimates (parton showering & hadronization may increase this effect)

Summary & Outlook

1. Physics motivation: Forward (di)jets in p-p at 14 TeV sensitive to

(i) low-x (~10^{-5}) & high-x (~0.5) gluon PDFs

(ii) non-DGLAP (BFKL, saturation) QCD evolution

2. Jet reconstruction performances in CMS HF calorimeter:

- Very similar performances for all algorithms (IC~Fast-k_T~SISCone).
- Very good p_T / η / φ resolutions& reconstruction above p_T~35 GeV/c.

3. Forward jets spectrum (full CMS simulation and reconstruction: $3<|\eta|<5$, 1 pb^{-1}):

- $d\sigma/dp_T$: ICONE~SISCone (FastkT ~20% less at low p_T).
- Sensitivity to MRST03-vs-CTEQ6 type -of PDFs differences in range p_T~35-50 GeV/c if JES controlled below 5%.

4. "Mueller-Navelet" dijets (Generator-level: $3<|\eta|<5$, 1 pb^{-1}):

PYTHIA / HERWIG (non-BFKL "benchmark"):

- For $\mathscr{L}$~1 pb^{-1} we expect: ~5000 (100) dijets separated by $\Delta\eta$~6 (9).
- Azimuthal decorrelation ($dN/d\Delta\phi$, $\langle\cos(\Delta\phi)\rangle$)

  PYTHIA/HERWIG: Maximum ~10%-30% azimuthal decorrelation

  BFKL: ~20%-50% azimuthal decorrelation effects expected.

Backup slides

Jet analysis procedure

- Full generation-simulation-reconstruction analysis in CMS
- Input Monte Carlos samples:

  - PYTHIA_6_4 & HERWIG: ~5 million events
  - Hard QCD processes:

Hard QCD processes:

11	$f_i f_j \to f_i f_j$
12	$f_i \bar{f}_i \to f_k \bar{f}_k$
13	$f_i \bar{f}_i \to gg$
28	$f_i g \to f_i g$
53	$gg \to f_k \bar{f}_k$
68	$gg \to gg$

PYTHIA

IPROC=1500
2→2 QCD

HERWIG

- Jets in range: full η, p_T ~ 20-200 GeV/c (weighted by pt-hat cross-section)

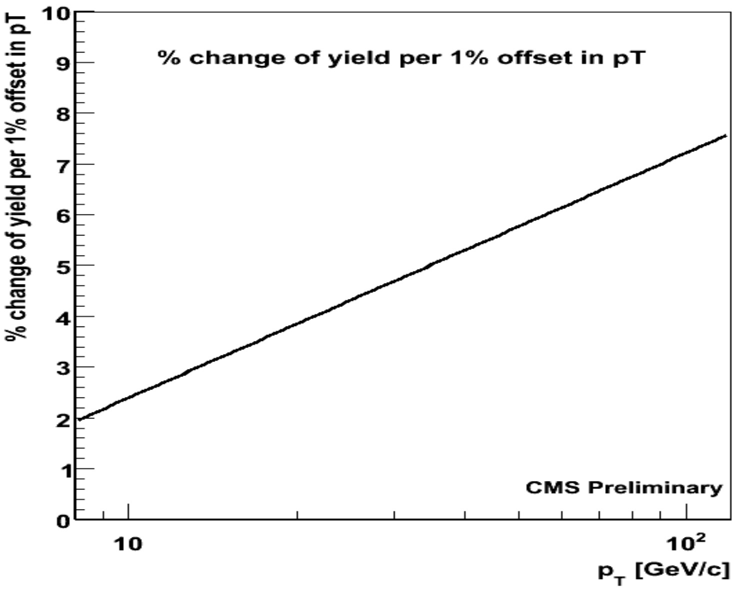
- 3 jet algorithms used:
  - Iterative Cone (R=0.5)
  - Fast-k_T (D=0.4)
  - SISCone (R=0.5)

Forward jet spectrum: syst. uncertainties

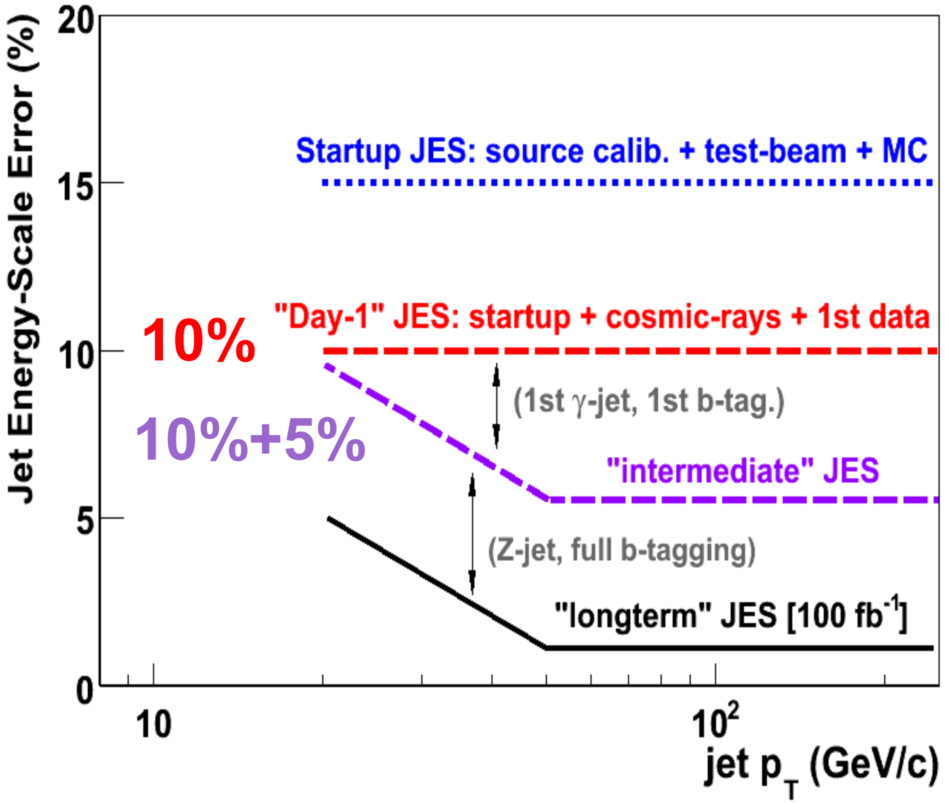
- Syst. uncertainties: jet-energy-scale (JES), E-resolution, lumi, pileup ...

  ⇒ Only JES & E-resolution important for PDF sensitivity.

- Energy-scale uncertainty propagates into yield-shift (steeply falling spectrum, wide bins)

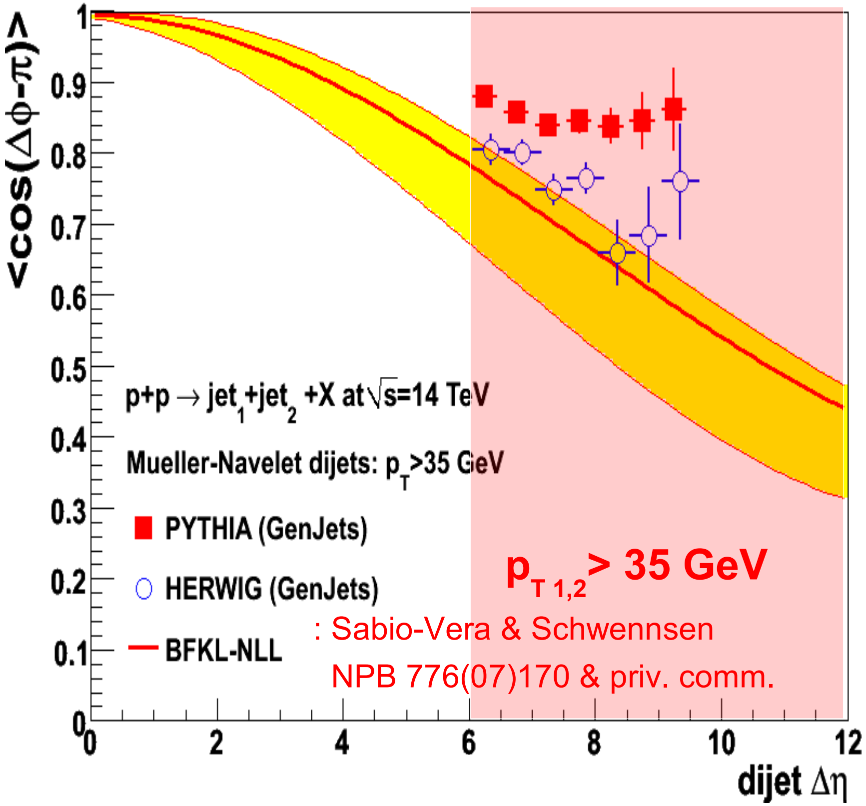


- 2 scenarios for JES calibration errors considered:

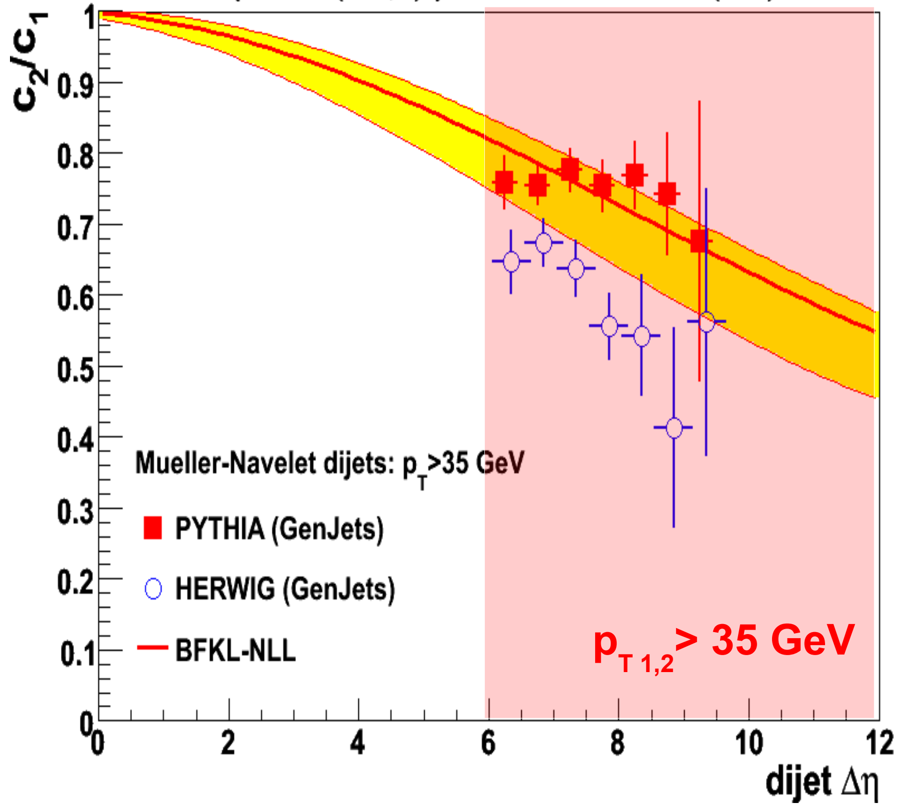


MN dijets: $\langle\cos(n\Delta\phi)\rangle$ & C_2/C_1 Pythia-Herwig-BFKL (Gen-Level)

- Average $\cos(n\Delta\phi)$ vs. $\Delta\eta$:



- $\frac{\langle\cos(m\phi)\rangle}{\langle\cos(n\phi)\rangle} = \frac{\mathcal{C}_m(\mathrm{Y})}{\mathcal{C}_n(\mathrm{Y})}$



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