Low-x QCD with forward jets in ATLAS, CMS & LHCb

EDS'09 International Conference

CERN, 3rd July 2009

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Overview

1. Introduction. Physics motivation:

   (1) Constrain low-x gluon PDF via fwd jets $d\sigma/dp_T$ $(3<|\eta|<5)$: data vs. pQCD

   (2) Study low-x QCD evolution via forward-backward "Muller-Navelet" dijets (cross-sections, azimuthal distributions, ...)

2. Jet reconstruction in the LHC forward detectors:

   - Acceptances (ATLAS, CMS, LHCb)
   - Jet perfomances: p_T, η, ϕ resolutions & reco efficiencies

3. Results (full-sim+reco, CMS):

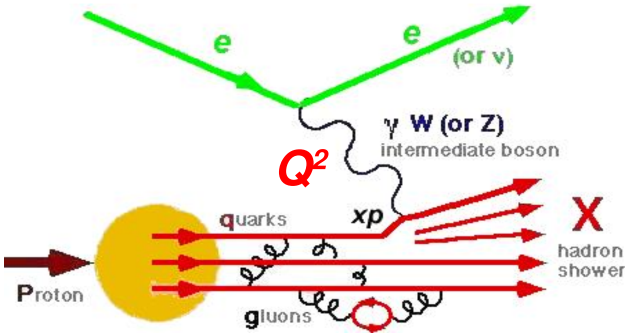
   (1) Inclusive forward jets $d\sigma_{jets}/dp_T$ vs. NLO: sensitivity to PDFs

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

4. Summary

Parton densities at low-*x*

- DIS *e*-p collisions probe distributions of partons in the proton:



Q^2 = "resolving power"

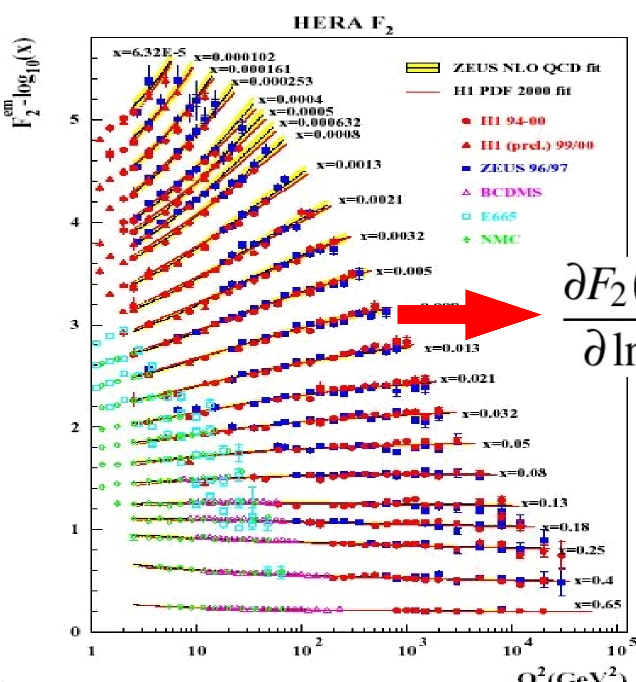
Bjorken x = momentum fraction carried by parton

$$\frac{d^2\sigma}{dx\,dQ^2} = \frac{2\pi\alpha^2}{xQ^4}\left[Y_+ F_2 \mp Y_- \cdot xF_3 - y^2 \cdot F_L\right]$$

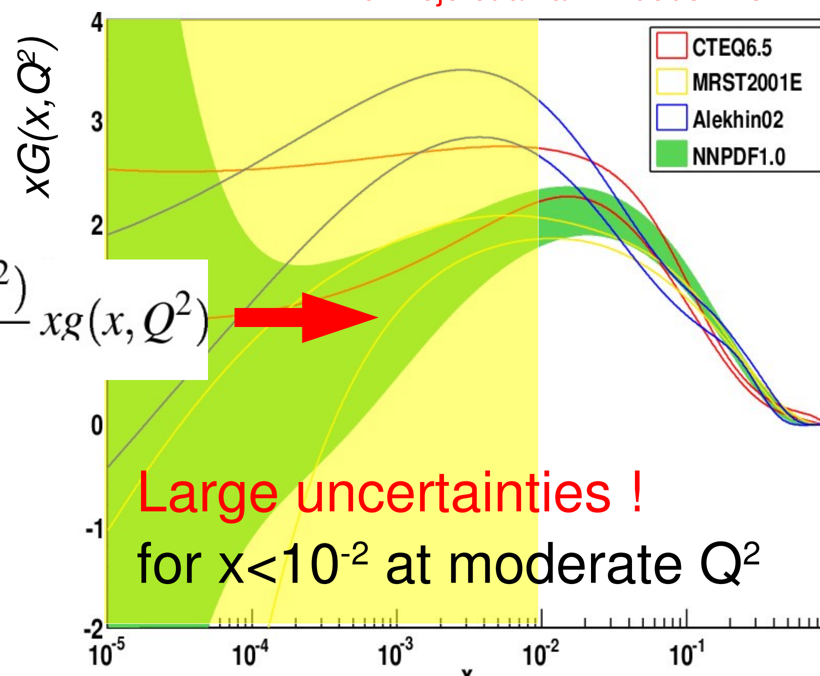
F_2, F_3, F_L = proton structure functions

- Gluons only indirectly (F_2 "scaling violations"):

J. Rojo *et al.* arXiv:0808.1231

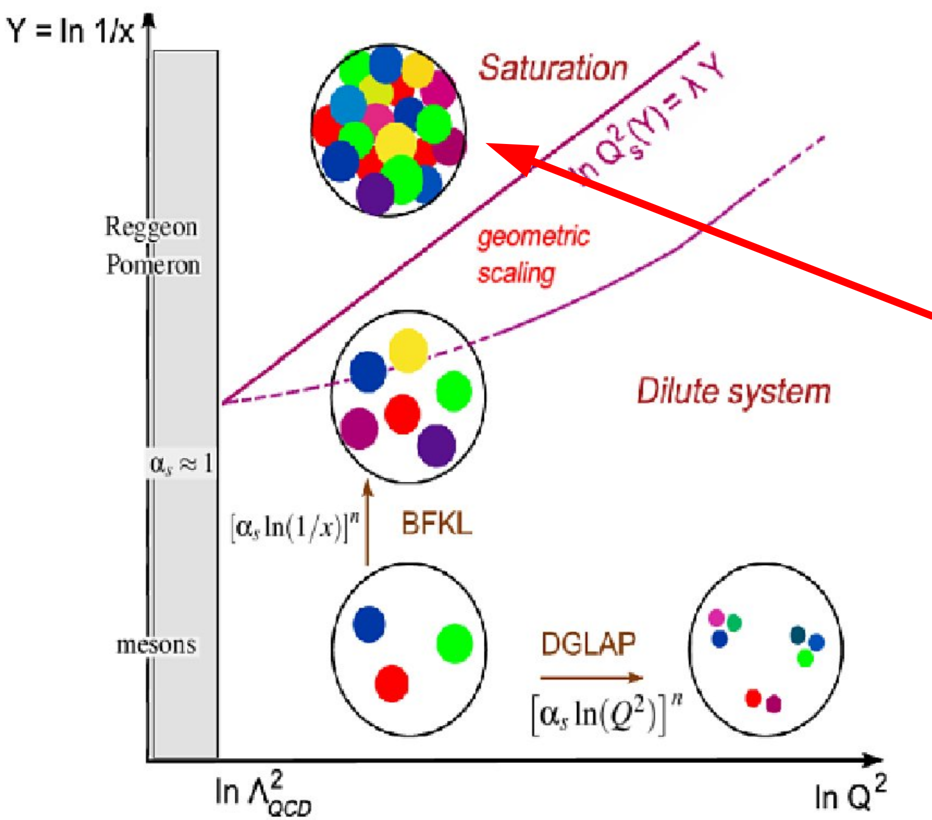


$$\frac{\partial F_2(x,Q^2)}{\partial \ln(Q^2)} \approx \frac{10\alpha_s(Q^2)}{27\pi}\, xg(x,Q^2)$$



(x,Q^2) evolution of PDFs

- **Q^2 - DGLAP** (k_T-order'd emission): $F_2(Q^2) \sim \alpha_s \ln(Q^2/Q_0^2)^n$, $Q_0^2 \sim 1$ GeV^2 [LT,coll.factoriz.]
- **x - BFKL** (p_L-ordered emission): $F_2(x) \sim \alpha_s \ln(1/x)^n$ [uPDFs, k_T-factoriz.]
- Linear equations – single parton radiation/splitting – cannot work at low-x



(i) Too high gluon density: nonlinear gluon-gluon fusion balances branchings.

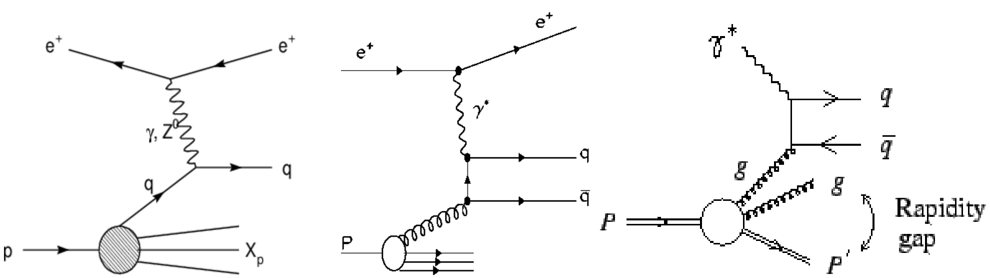
(ii) pQCD (collinear & k_T) factorization assumptions invalid (HT, no incoherent parton scatt.).

(iii) Violation of unitarity even for $Q^2 >> \Lambda^2$ (too large perturbative cross-sections)

- Non-linear effects may "leak" to higher Q^2 ("geometric scaling") region

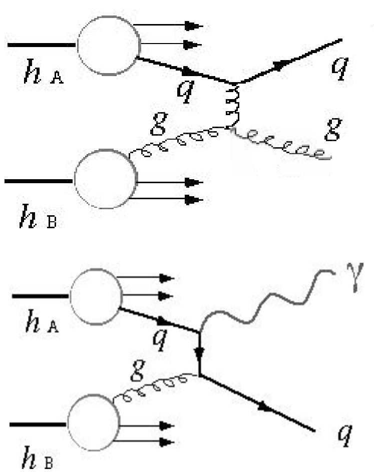
Experimental access to low-x gluon PDF

- Perturbative processes:
  - e-p: $\partial \ln F_2/\partial \ln Q^2$, F_L, heavy-Q, diffractive $Q\bar{Q}$:

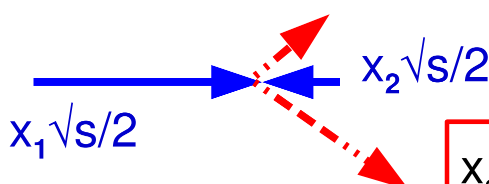


…

  - p-p: (di)jets, prompt γ, heavy-Q, ...:

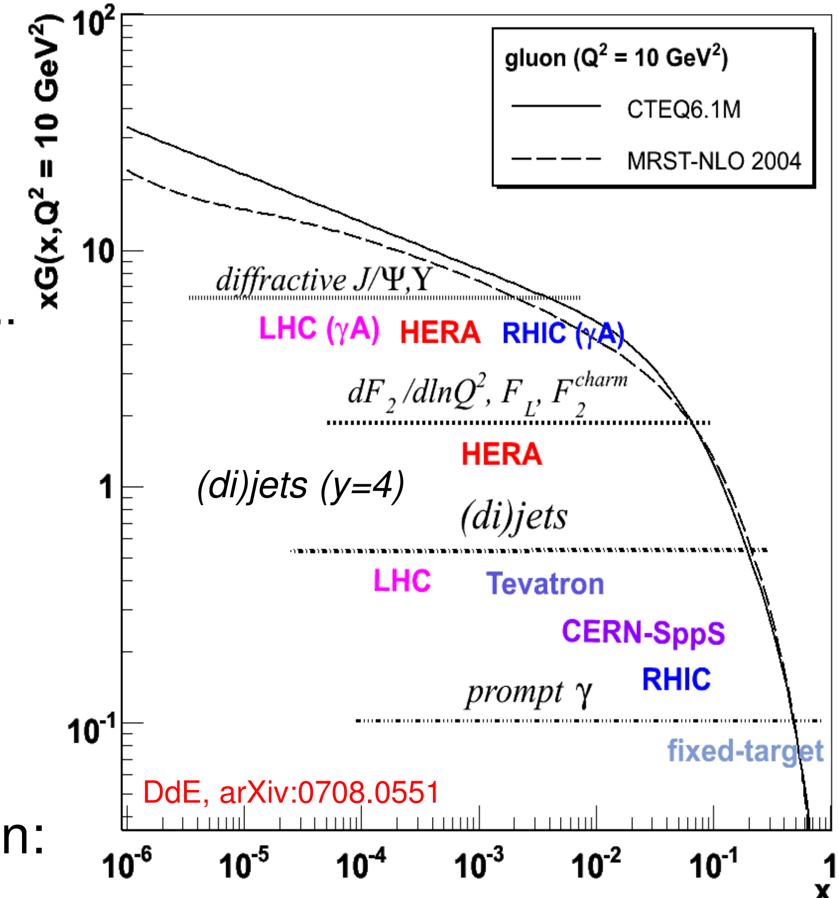


  - Forward production:



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

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



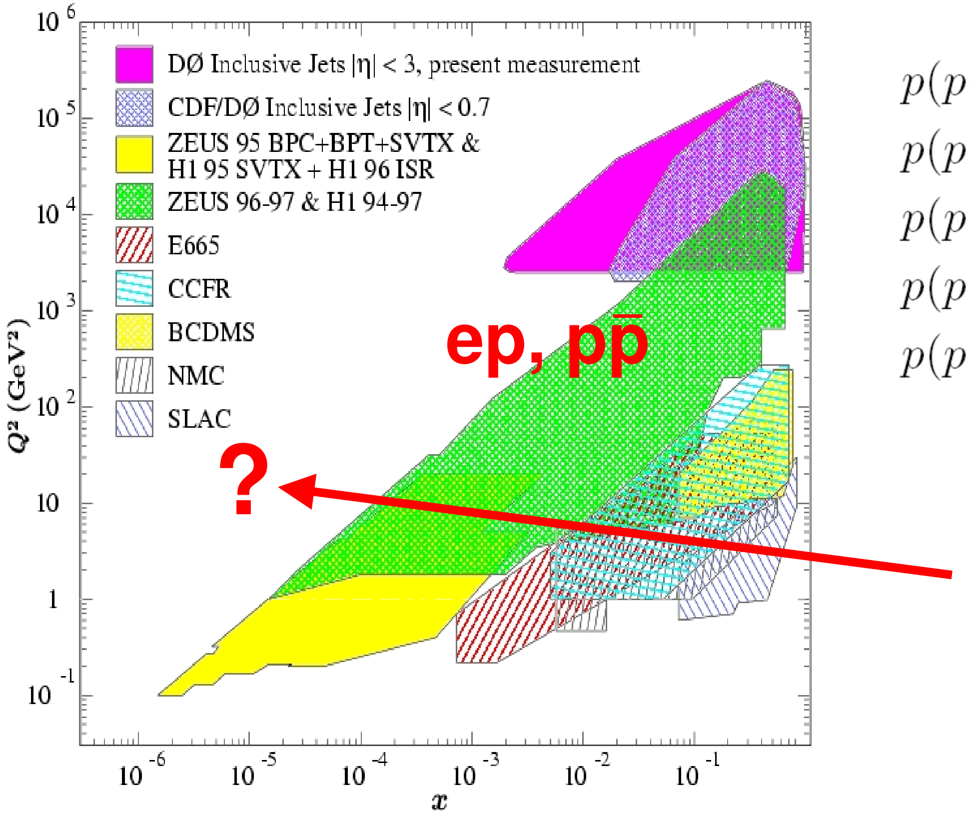
Low-*x* studies at the LHC

- p-p @ 14 TeV :

(1) At y=0, $x=2p_T/\sqrt{s}\sim10^{-3}$ (domain probed at HERA,Tevatron). Go fwd. for $x<10^{-4}$

(2) Saturation momentum: $Q_s^2\sim$ 1 GeV^2 (y=0), 3 GeV^2 (y=5)

(3) Very large perturbative cross-sections:



$$p(p_1)+p(p_2)\rightarrow \text{jet}+\gamma+\ X$$ Prompt γ

$$p(p_1)+p(p_2)\rightarrow l\bar{l}+\ X$$ Drell-Yan

$$p(p_1)+p(p_2)\rightarrow \text{jet}_1+\text{jet}_2+\ X$$ Jets

$$p(p_1)+p(p_2)\rightarrow \text{Q}+\bar{\text{Q}}+\ X$$ Heavy flavour

$$p(p_1)+p(p_2)\rightarrow W/Z+\ X$$ W,Z production

LHC forward rapidities:

e.g. y ~ 6, Q ~ 10 GeV

x down to 10^{-6} !

Forward detectors at the LHC

- Most of phase-space $\Delta y \sim 2\times\ln(\sqrt{s})/m_p \sim 20$ covered:

  1st time in a collider !

- Calorimeters:

  CMS/ATLAS: up to $|\eta|\sim 6.6$

  LHCb: $2<\eta<5$

- Muon spectrometers:

  LHCb: $2<\eta<5$

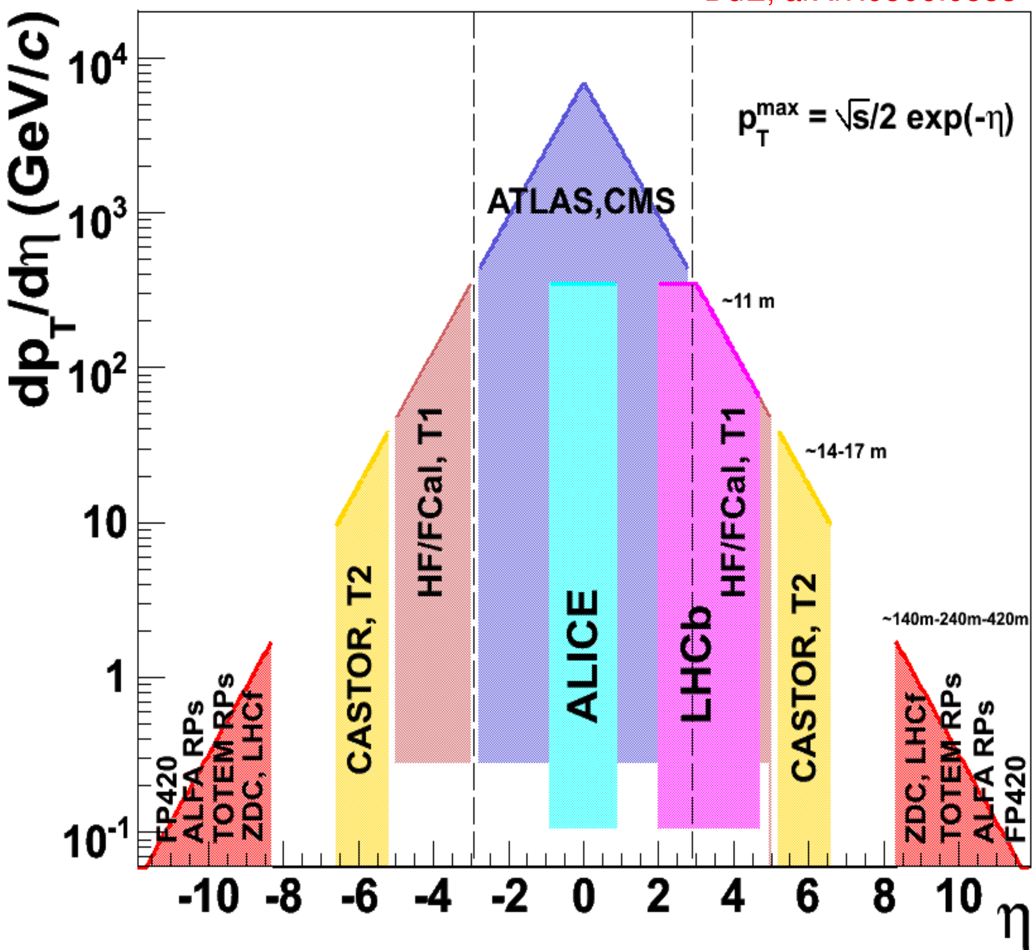
  ALICE: $2.5<\eta<4$

- Trackers/PID/2nd vtx:

  LHCb: $2<\eta<5$

  (TOTEM partially)

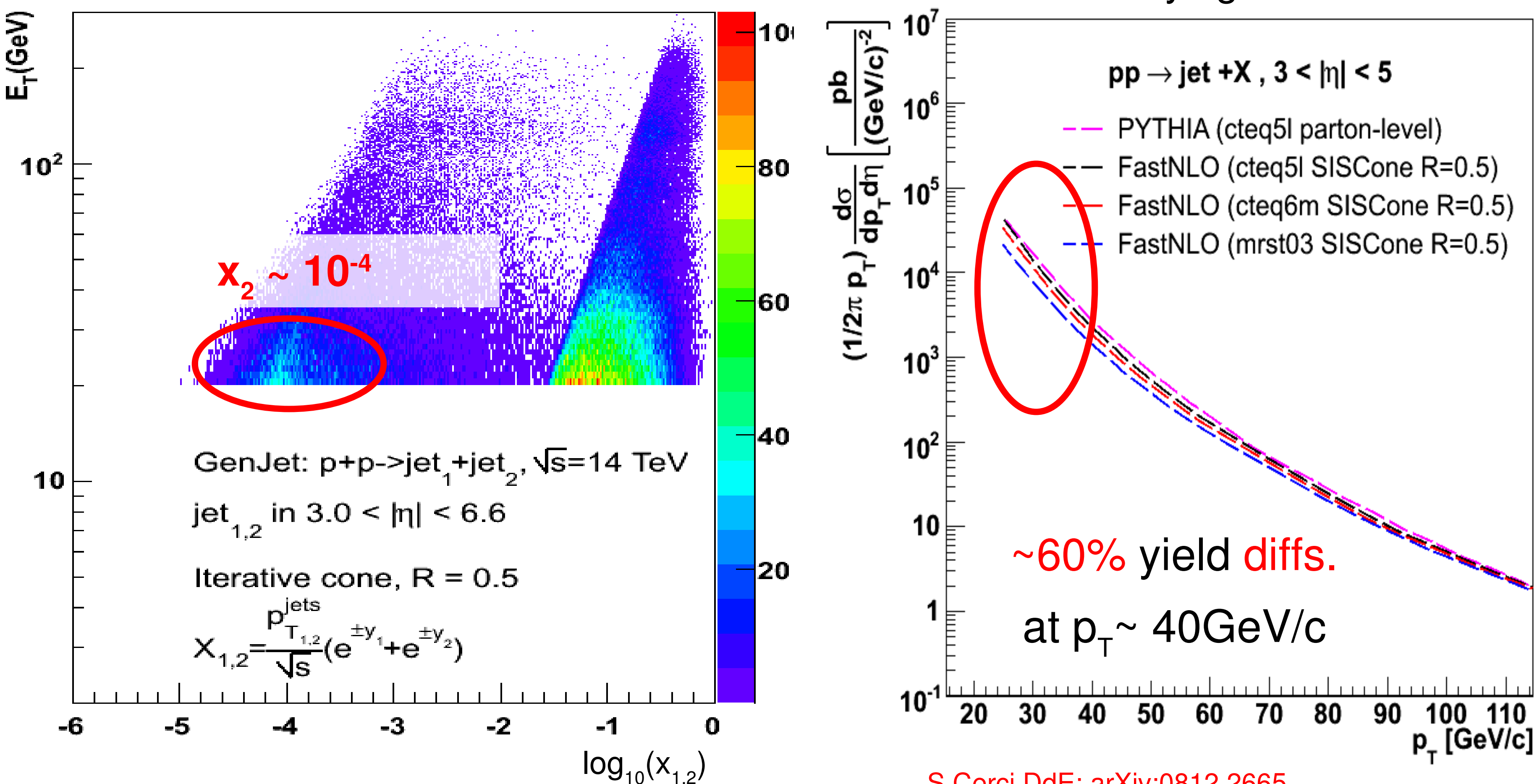
DdE, arXiv:0806.0883



Observable (1): Gluon PDF via fwd. jets

- Jets with $p_T \sim$20-100 GeV/c at forward rapidities ($3<|\eta|<5$) probe $x_2 \sim 10^{-4}$: PDF cross-checks and/or global-fit analyses.

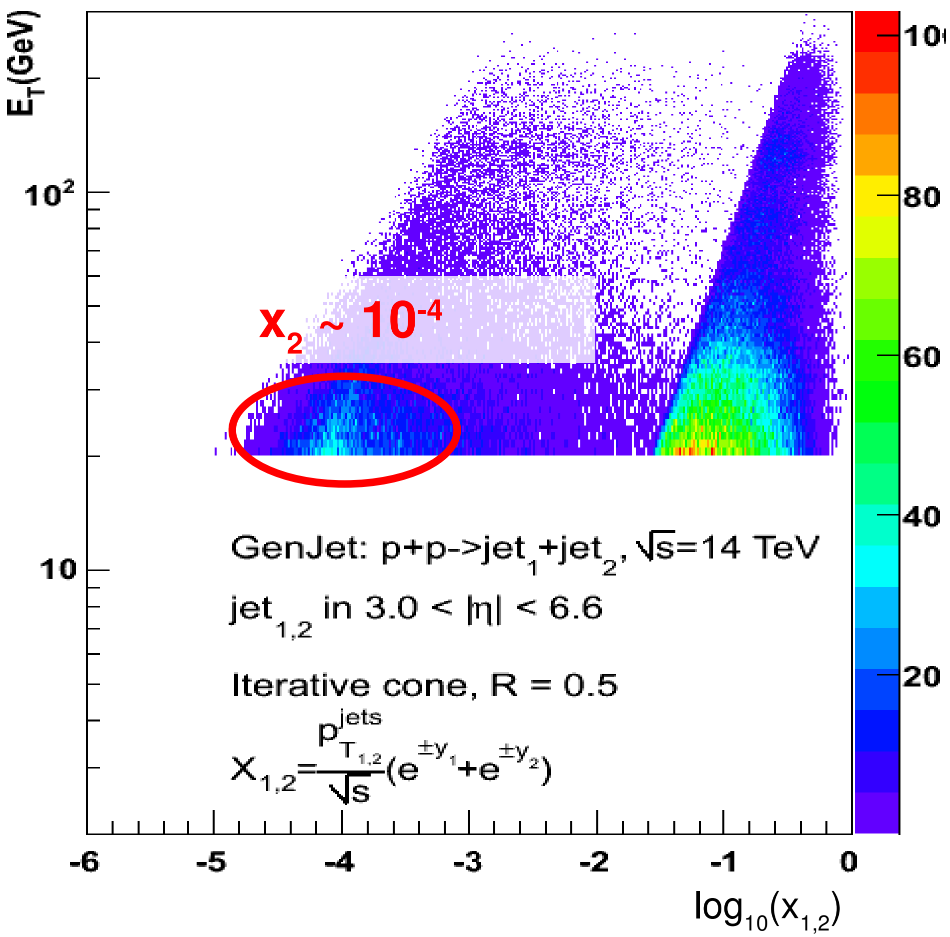
varying PDFs:



S.Cerci,DdE: arXiv:0812.2665

Observable (1): Gluon PDF via fwd. jets

- Jets with p_T ~20-100 GeV/c at forward rapidities ($3<|\eta|<5$) probe $x_2 \sim 10^{-4}$: PDF cross-checks and/or global-fit analyses.



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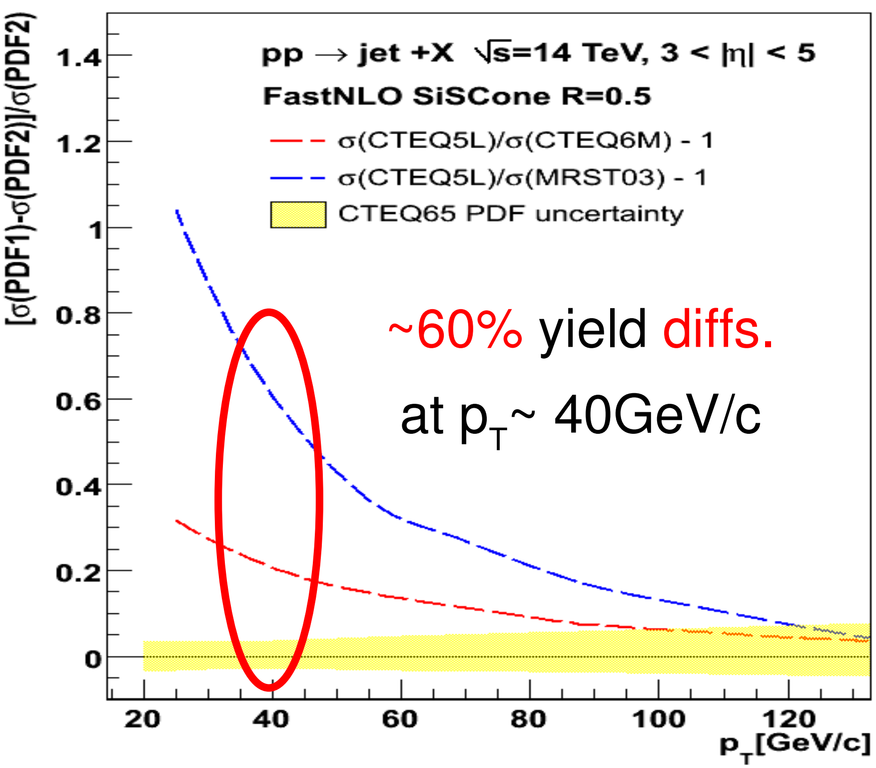

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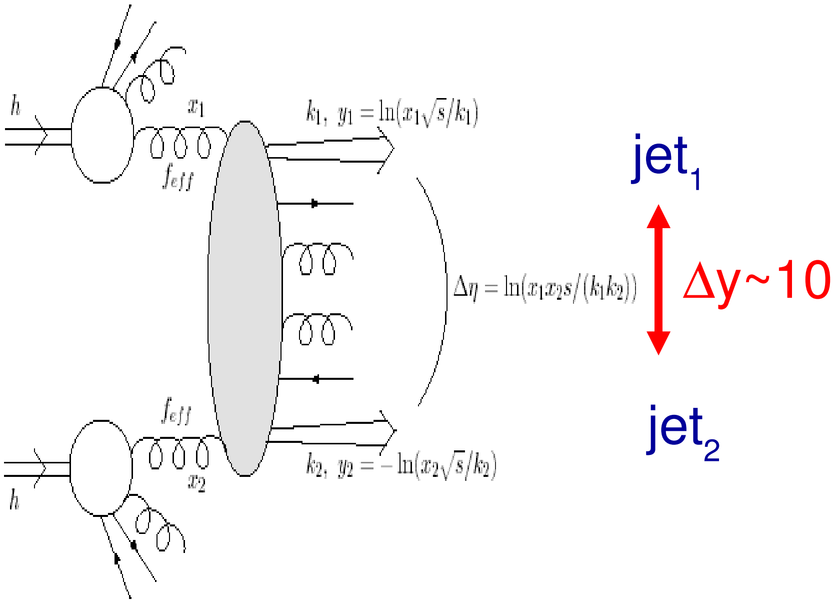
Observable (2): Low-x QCD via fwd-back. dijets

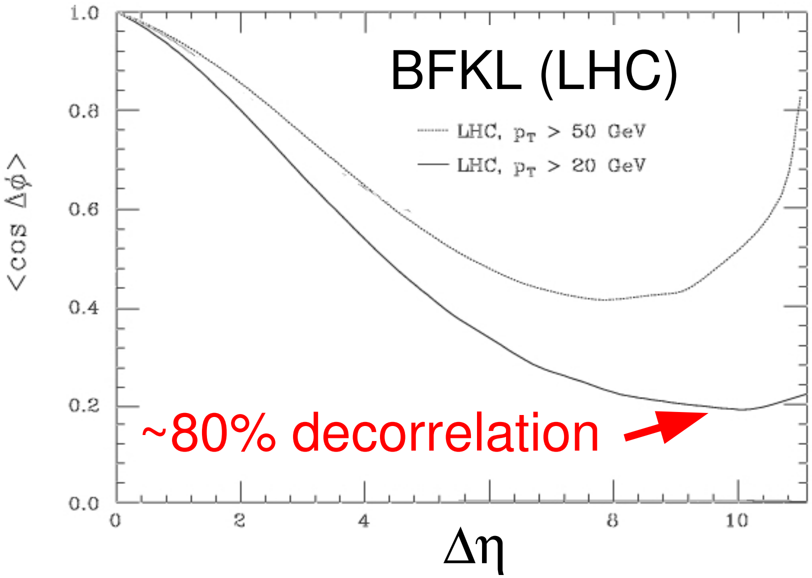
- Mueller-Navelet dijets with large y separation very sensitive to low-x QCD evolution (testing ground for BFKL):



Extra BFKL radiation between the 2 jets smooths out back-to-back topology

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

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



[DelDuca, Schmidt], [Orr, Stirling]
[A.Sabio-Vera, F.Schwennsen]
[C.Marquet, Royon] [E. Iancu et al.]

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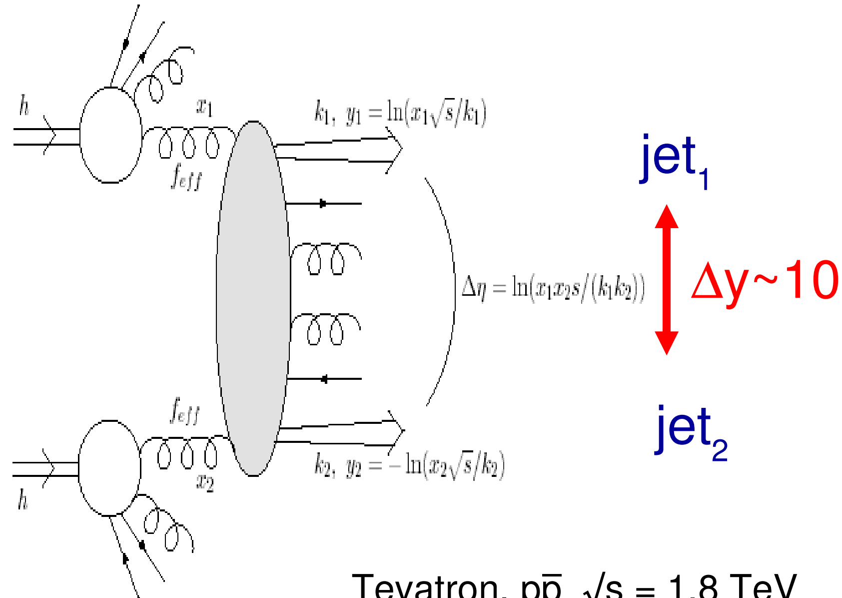
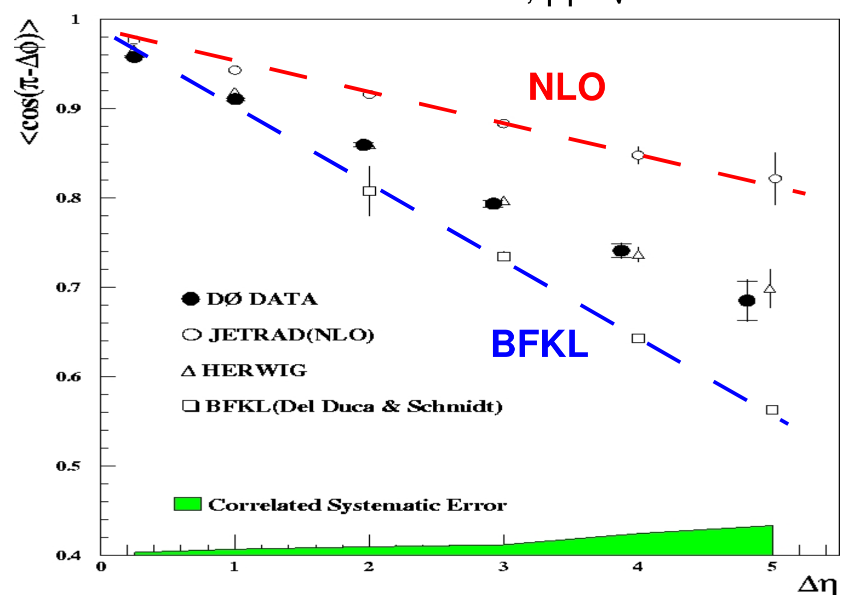


- Increased azimuthal decorrelation with increasing Δy (w.r.t. DGLAP collinear-factorization):

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



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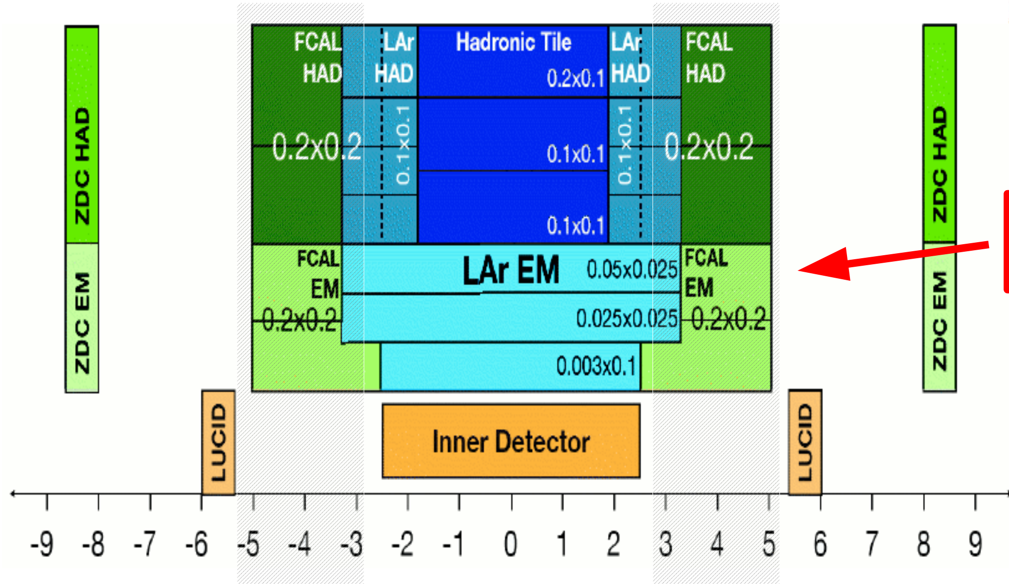
[C.Marquet, Royon] [E. Iancu et al.]

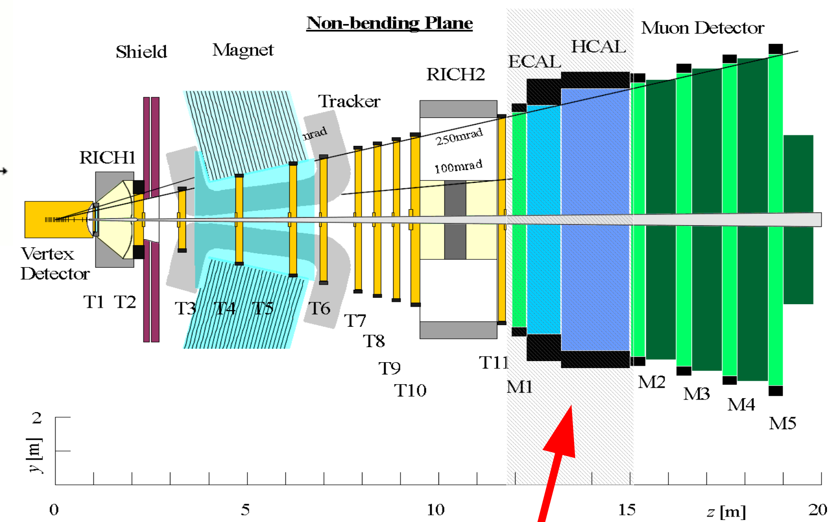
[D0 Collab, PRL77(97)595]

2. Forward jet reconstruction perfomances at the LHC

LHC forward (EM/HAD) calorimeters

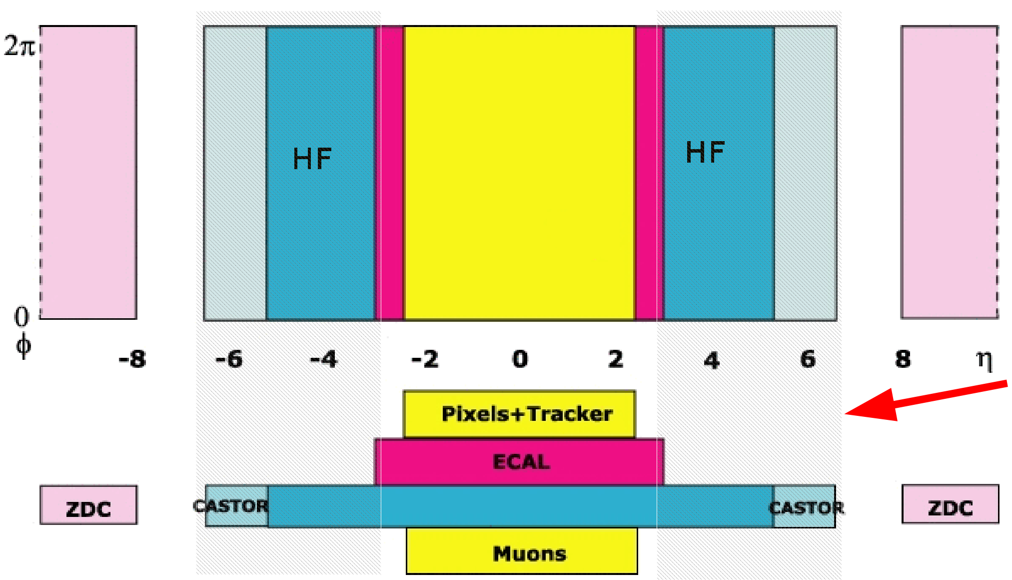


3 < |η|< 5



2 < η < 5

Note: also tracking !



3 < |η|< 6.6

ATLAS/CMS/LHCb: Jet algorithms

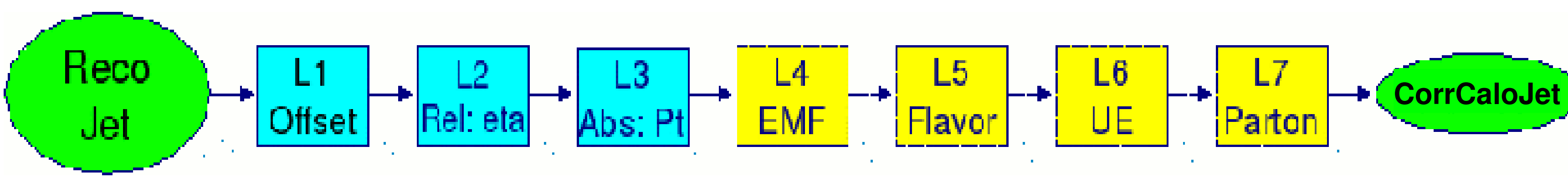
- 3 std. jet algos (ICone, kT,SISCone) available in official codes:

	Iterative Cone	SISCone	Fast-k_T
Jet size (*)	$R = 0.5$	$R = 0.5$	$D = 0.4$
Alias	IC05	SIS05	FastKt04
Tower thresholds	$E_T > 0.5$ GeV	$E_T > 0.5$ GeV	$E > 1$ GeV
Cell thresholds	Scheme B		
Seed threshold	$E_T > 1$ GeV	NA	NA

Table 3: Parameters for the jet reconstruction algorithms used in this work.

(*) Note: smallish radii chosen (R=0.5~D=0.4) to minimize UE (fwd.)

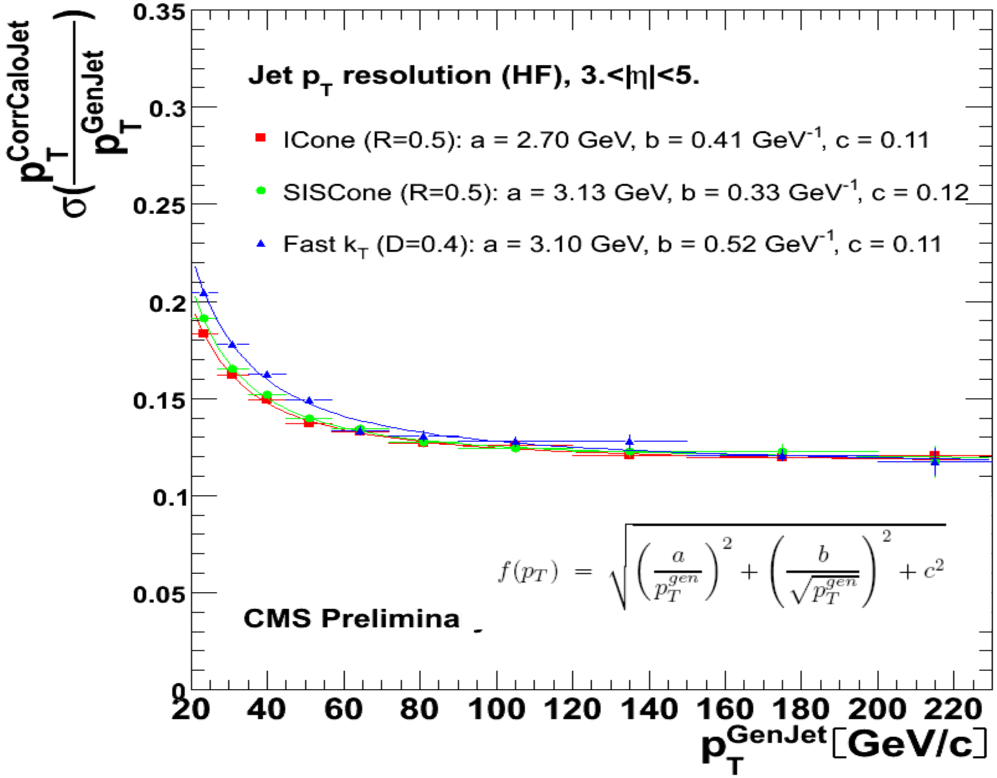
- LHCb: Calo+Tracks. Secondary vtx. required (focus on b-jets so far).
- ATLAS/CMS: CaloJets only (fwd). Std jet energy corrections applied:



ATLAS/CMS: forward jet resolutions

[CMS plots. Similar results for ATLAS]

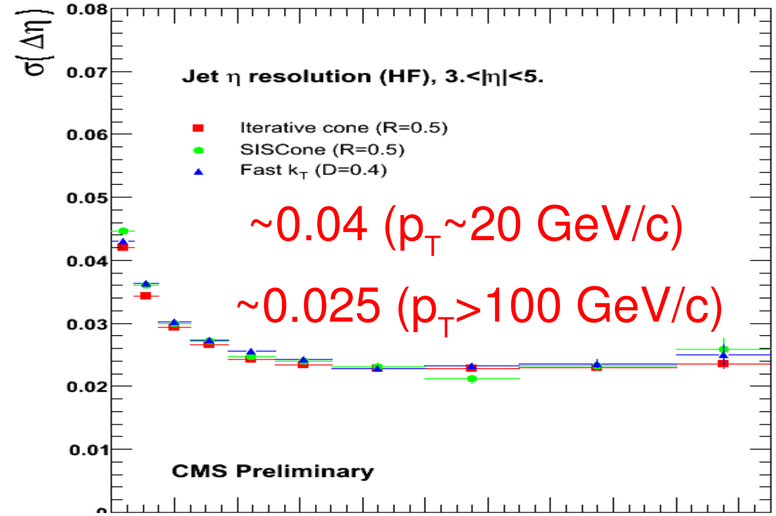
- p_T resolution :



~20% (p_T~20 GeV/c), ~12% (p_T>100 GeV/c)

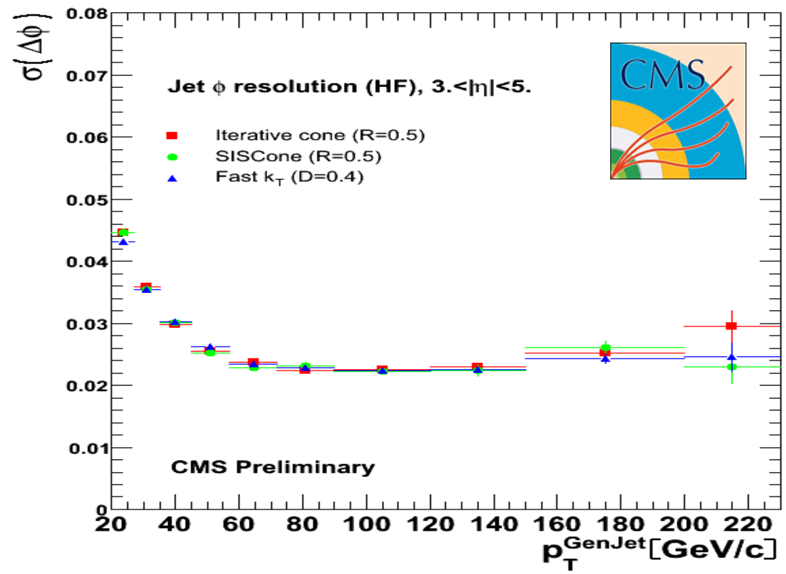
- ICone~Fast-kT~SISCone.

- Position η-ϕ resolution :



~0.04 (p_T~20 GeV/c)

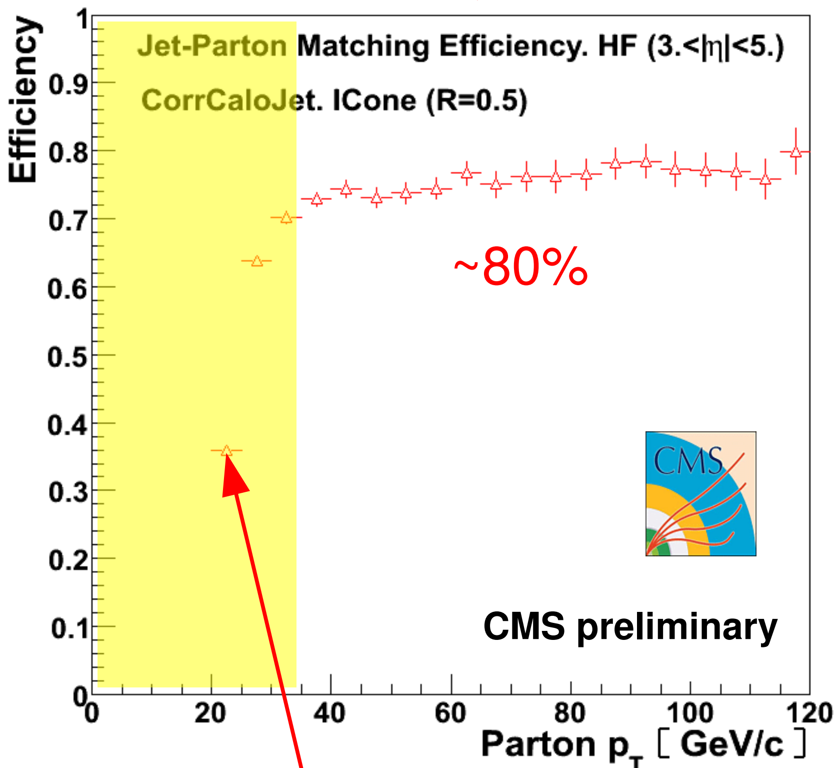
~0.025 (p_T>100 GeV/c)



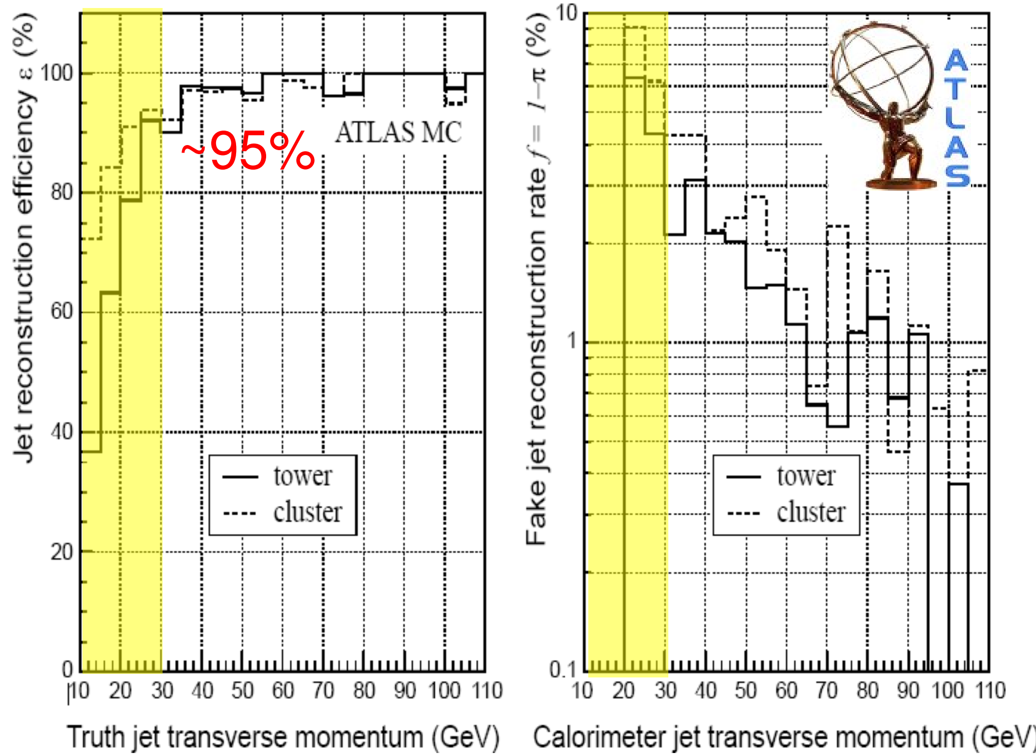
ATLAS/CMS: fwd. jet reco efficiency

- Good reconstruction efficiency above p_T ~35 GeV/c:

S.Cerci,DdE: arXiv:0812.2665



ATLAS-TDR CERN-OPEN'08-20



~10% fake rate

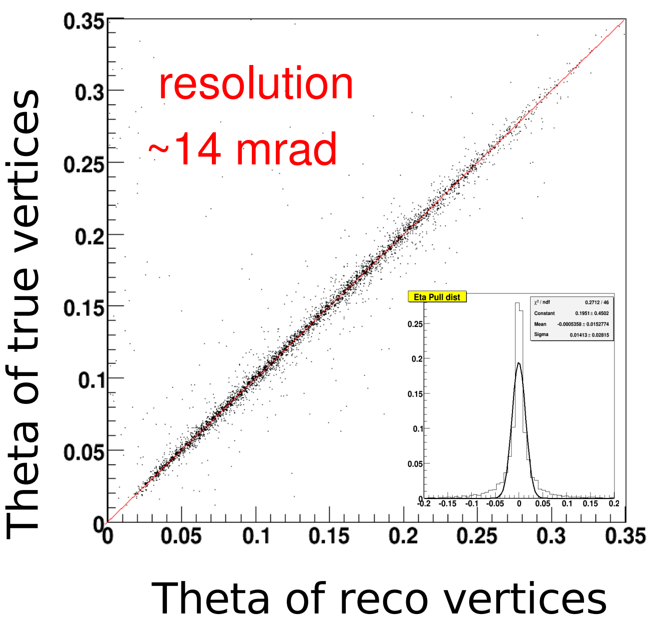
p_T~20 GeV/c: ~50% fake jets

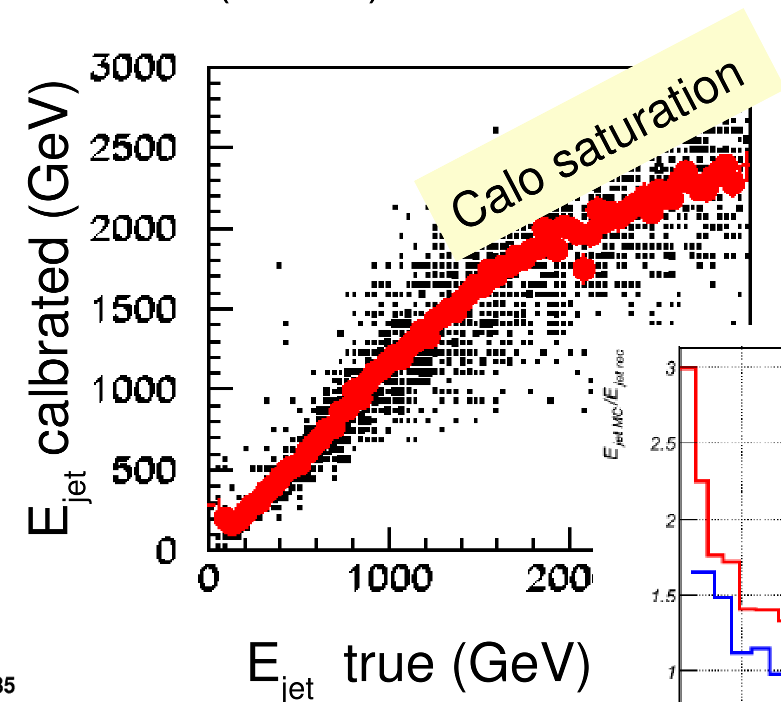
- Fake jets <35 GeV/c: clustered underlying event, beam-remnants, noise ...

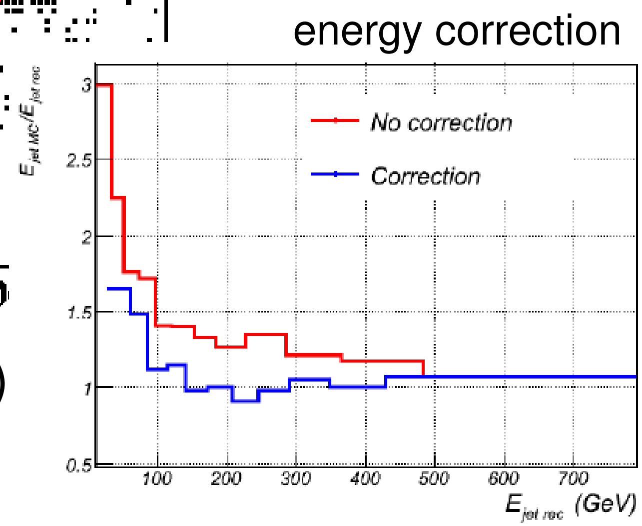
LHCb: fwd. jet reco performances

Marco Musy [LHCb]

- Focus on b-jets (H $\rightarrow$ bbar in VH associated production) so far.
- Algos: kT (D=0.75) & seed cone (R=0.7). Neural-network for b-jet selection







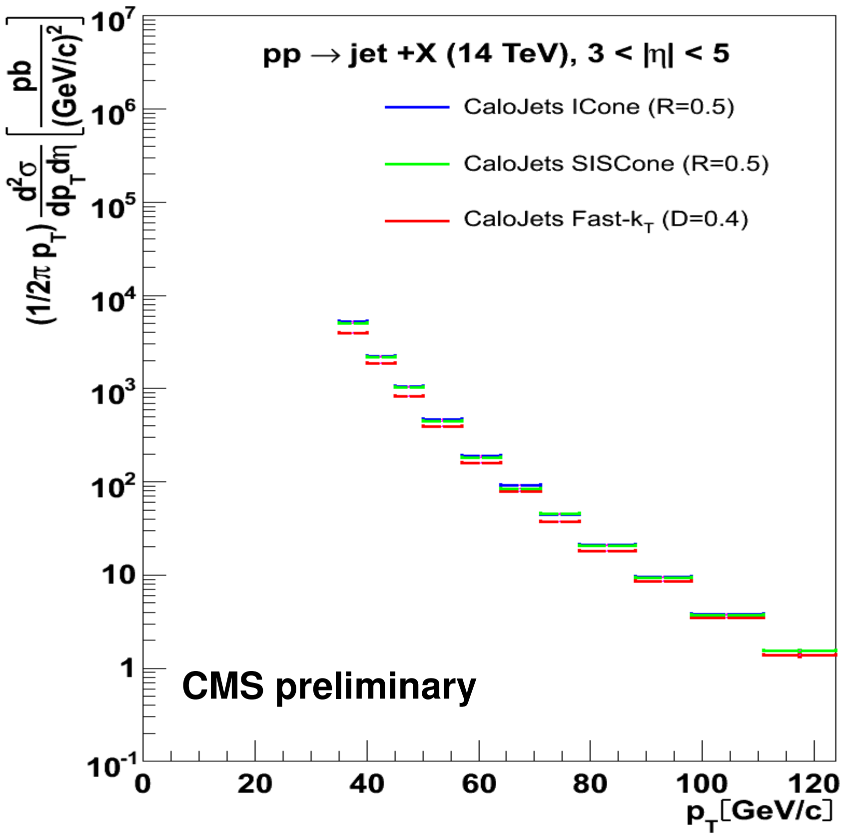
- Nice jet-reco capabilities (tracking): vertexing, position resol., ... Calo saturation is an issue only at high-p_T. Interesting potential for fwd light-q,g jets.

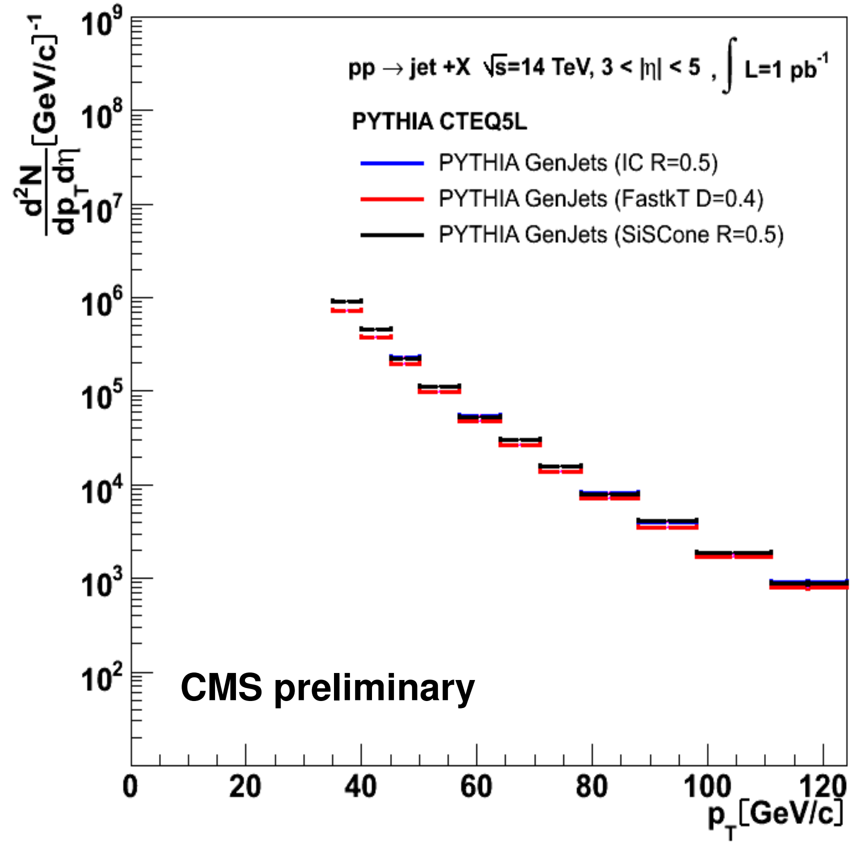
3. Fwd. jet spectrum (CMS): PDF sensitivity

Fwd jet spectrum (1 pb^{-1}): algos comparison

S.Cerci,DdE: arXiv:0812.2665

- Invariant cross-sections : ICone, SiSCone, Fast-kT
- Yields: ~1M fwd. jets with p_T>35 GeV/c



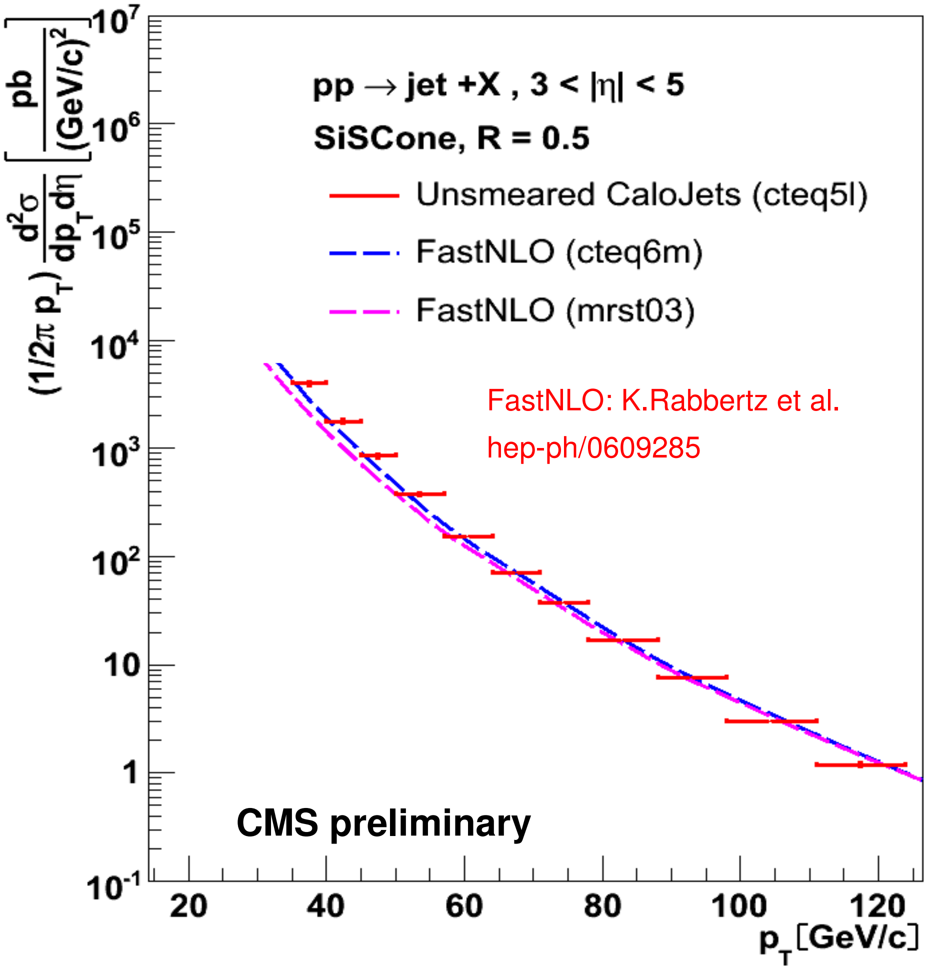


- SISCone & IterativeCone yields are very similar.
- Fast-kT is 20%-25% lower than cone algorithms below $p_T \approx$ 80 GeV/c

Fwd. jet spectrum (1 pb^{-1}): uncertainties

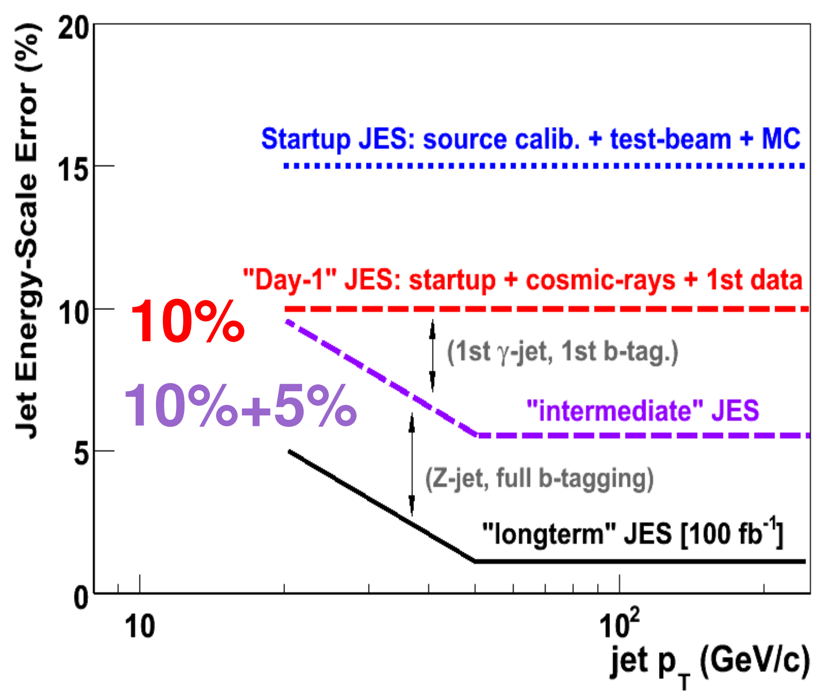
S.Cerci,DdE: arXiv:0812.2665

- Invariant cross-sections: CorrCaloJets vs. NLO-MRST03,CTEQ6M
- Small point-to-point errors: statistical + 2%-5% E-resolution unsmearing



- Main systematic uncertainty: jet-energy-scale (JES).

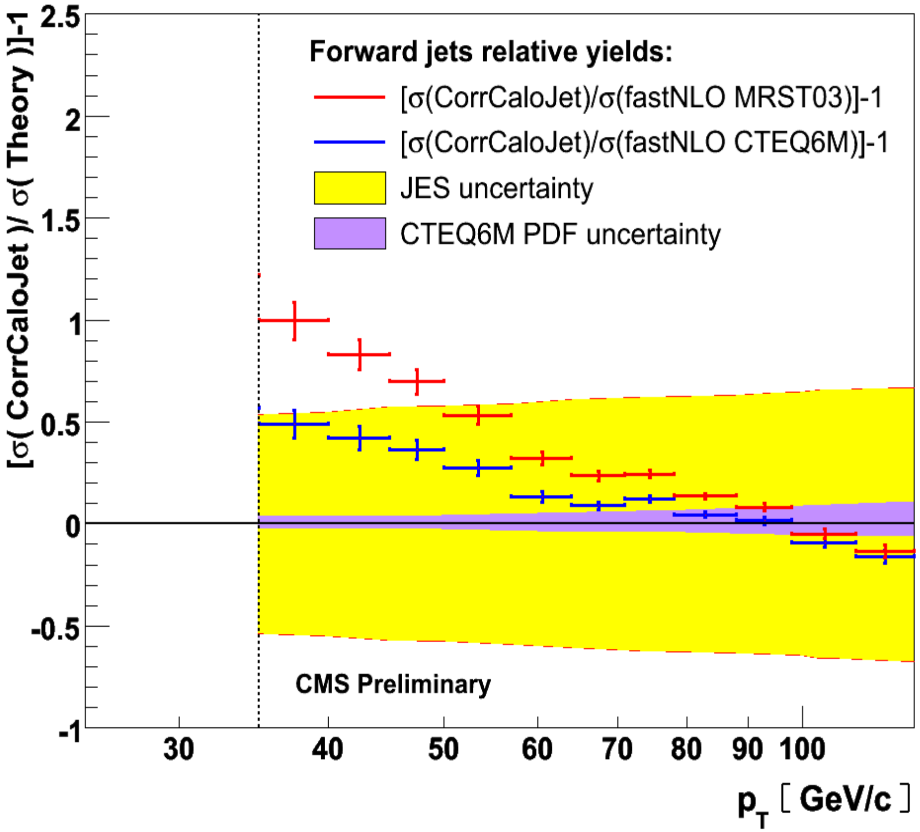
2 calibration scenarios:

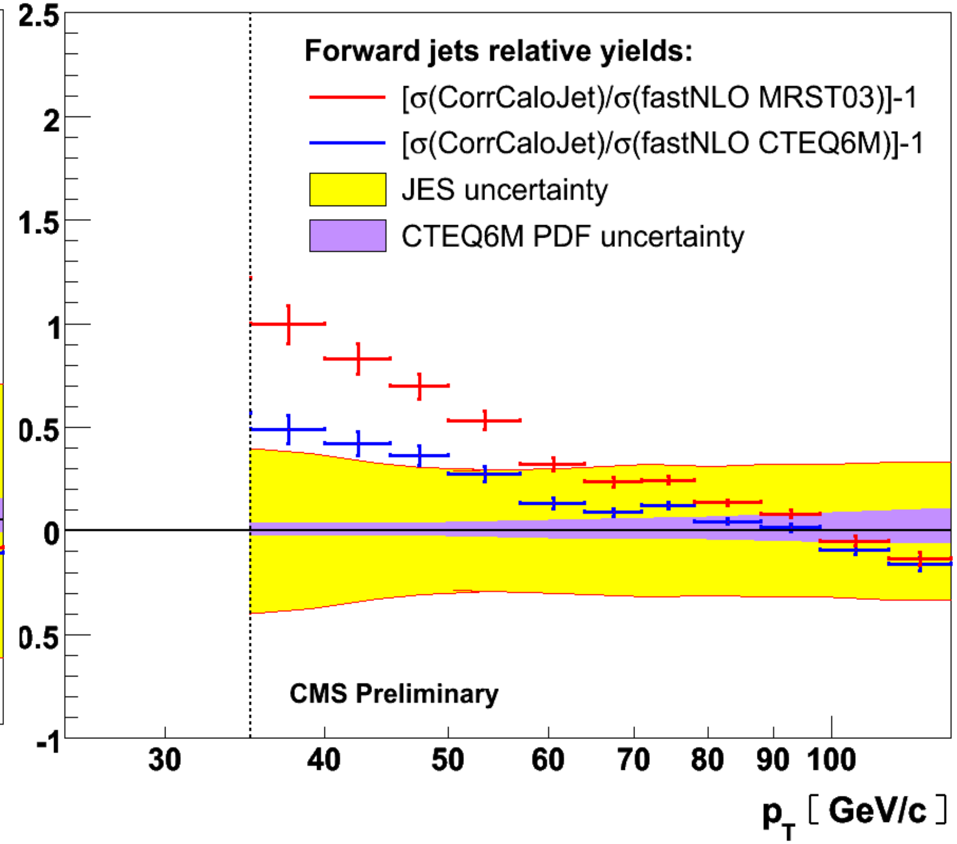


Fwd. jet spectrum (1 pb^{-1}): PDF sensitivity

S.Cerci,DdE: arXiv:0812.2665

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

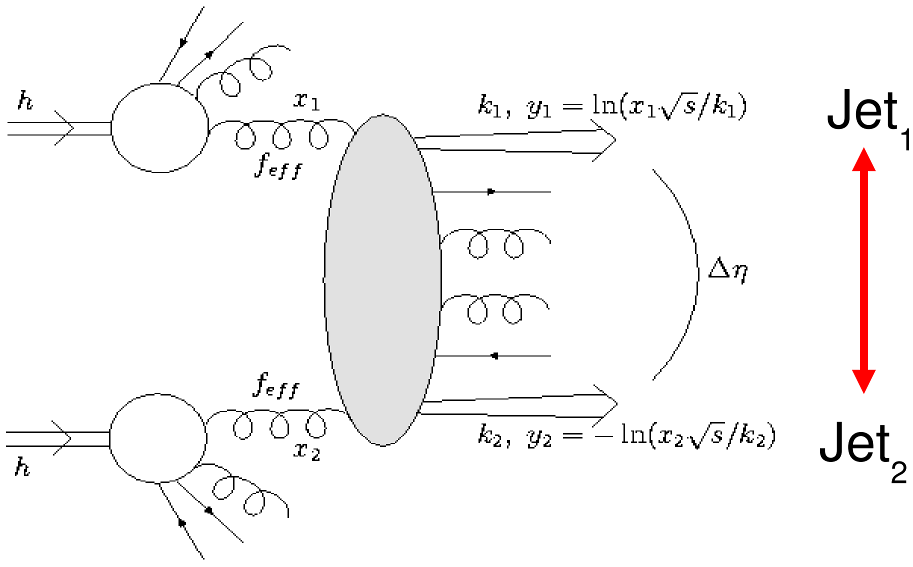




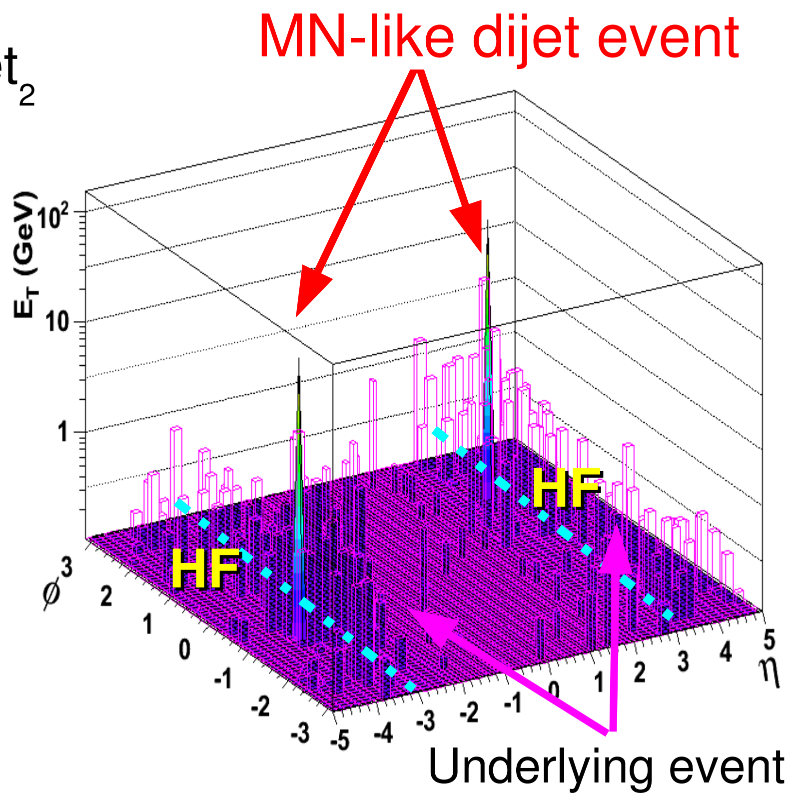
- JES scenario-1 (>50% errors): No PDF sensitivity
- JES scenario-2 (30%-40% errors): PDF sensitivity for <60 GeV/c

4. ”Muller-Navelet” dijets (CMS): yields, azimuthal decorrelation

Muller-Navelet dijets: kinematic cuts

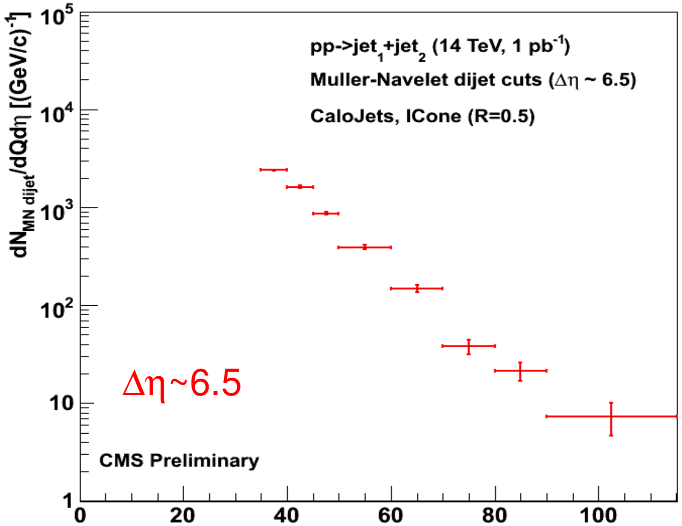


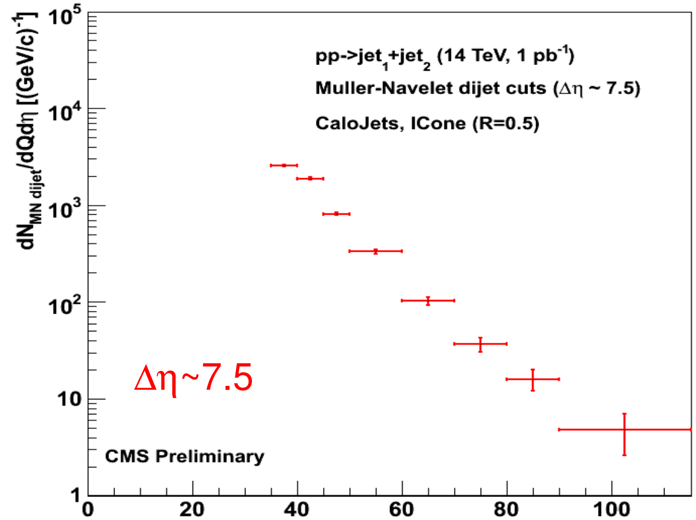
- 2 forward jets : $3. < |\eta| < 5.$
- Moderately hard: $p_T > 35$ GeV
  (good parton-jet match, trigger effic.)
- Similar p_T (minimize DGLAP rad.):
  $|p_{T1}-p_{T2}| < 5$ GeV
- Jets in opposite: $\eta_1 * \eta_2 < 0.$



MN dijets: Expected yields (1 pb^{-1})

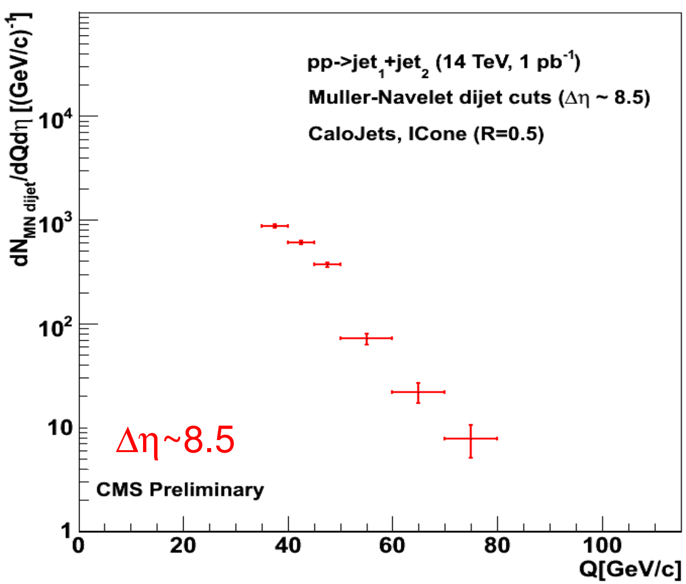
- Stats: ~5000(200) Mueller-Navelet-type dijets separated by $\Delta\eta$~6 (9).

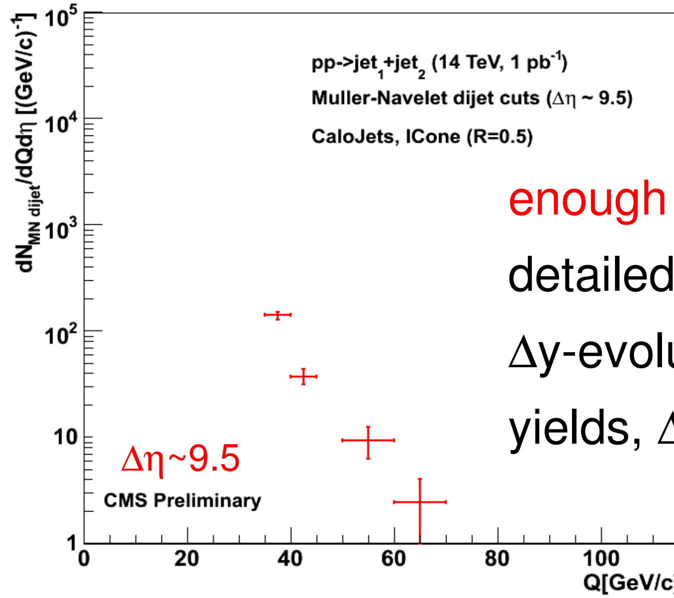




$p_{T\,1,2}$> 35 GeV/c

S.Cerci,DdE: arXiv:0812.2665



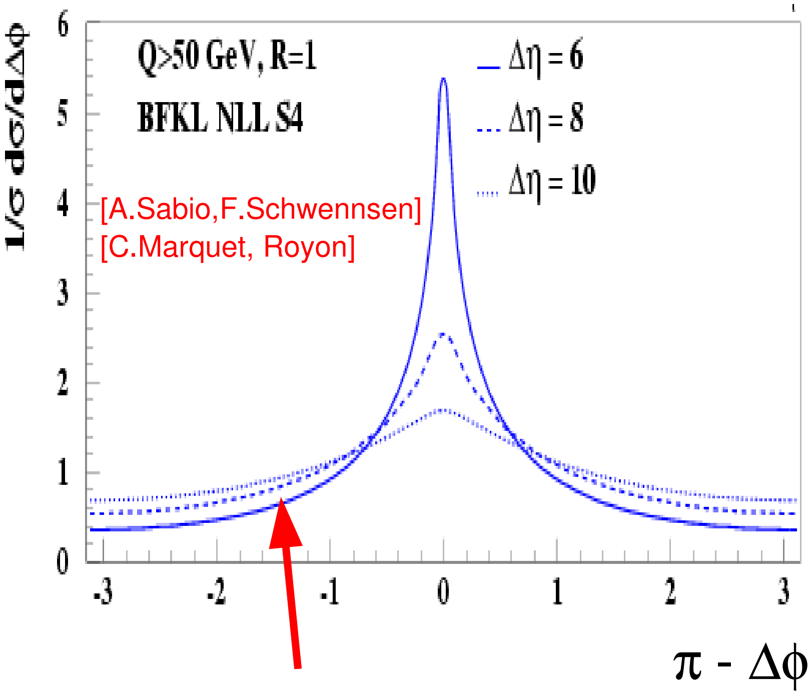


enough stats for detailed studies of Δy-evolution in $|\Delta\eta|$=6-9: yields, $\Delta\phi$ decorrelation

MN dijets: azimuthal decorrelation

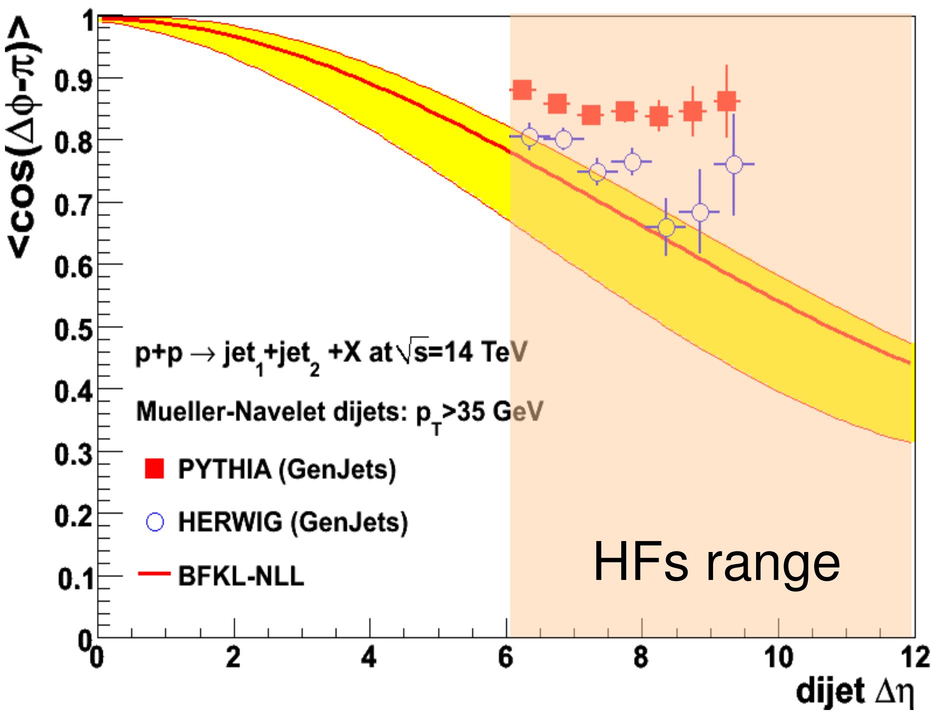
S.Cerci,DdE: arXiv:0812.2665

- BFKL predictions (parton-level):



- Extra radiation enhances azimuthal (back-to-back) decorrelation.

- PYTHIA/HERWIG vs BFKL:



HERWIG more decorrelation (~15%) than PYTHIA but ~20% less than BFKL analytical estimates (parton showering & hadroniz. will still increase this effect).

Summary

1. Physics motivation:

   Forward (di)jets in p-p at 14 TeV sensitive to:

   (i) low-x gluon PDFs, (ii) non-DGLAP (BFKL, saturation) QCD evolution.

2. Jet reco performances in forward calorimeters:

   ✶ Similar for all algos (cone,kT) for smallish jet radius (R=0.5~D=0.4)

   ✶ Good reconstruction for p_T >35 GeV/c.

3. Forward jets single spectrum:

   ✶ Large stats. (~1M jets, 1pb^{-1}) but large syst. error (>30%) from JES.

   ✶ Sensitivity to PDFs differences (p_T~35-60 GeV/c) iff JES controlled below 5%.

4. "Muller-Navelet" dijets:

   ✶ Stats ($\mathcal{L}$~1 pb^{-1}): ~5000 (200) dijets separated by $\Delta\eta$~6 (9).

   ✶ "Normal" azimuthal decorrelations: ~10-20% (hadronization+FS radiation) ~10-20% (exp. reco effects). HERWIG ~15% more decorrelation than PYTHIA.

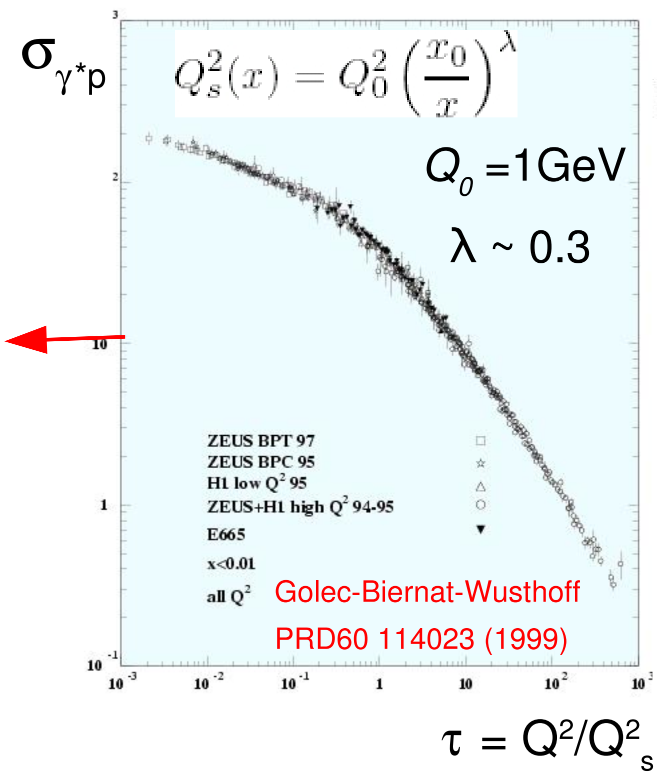
   ✶ Enhanced BFKL decorrelation should be identifiable in the data (<cos($\Delta\phi$)>)

Backup slides

Gluon saturation hints at HERA

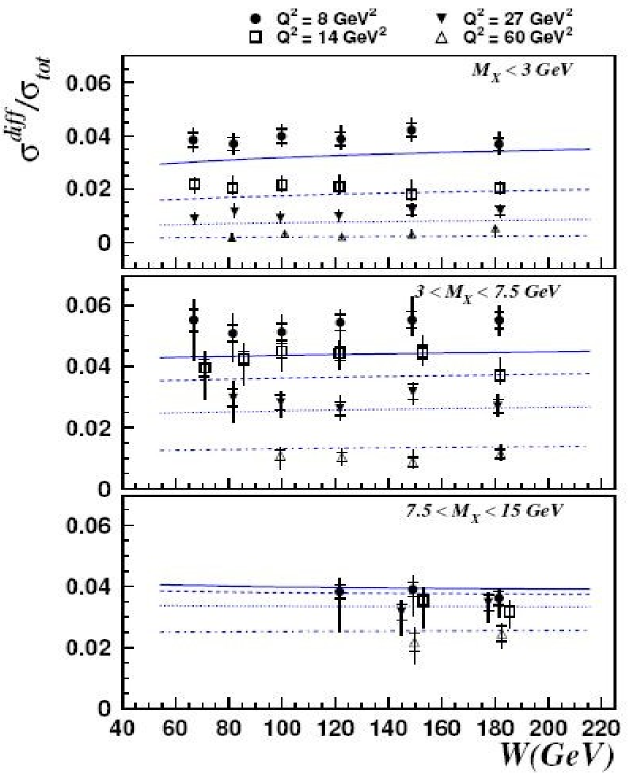
- DGLAP fits most of e-p data. Saturation models explain better a few cases:

(1) "Geometric scaling"



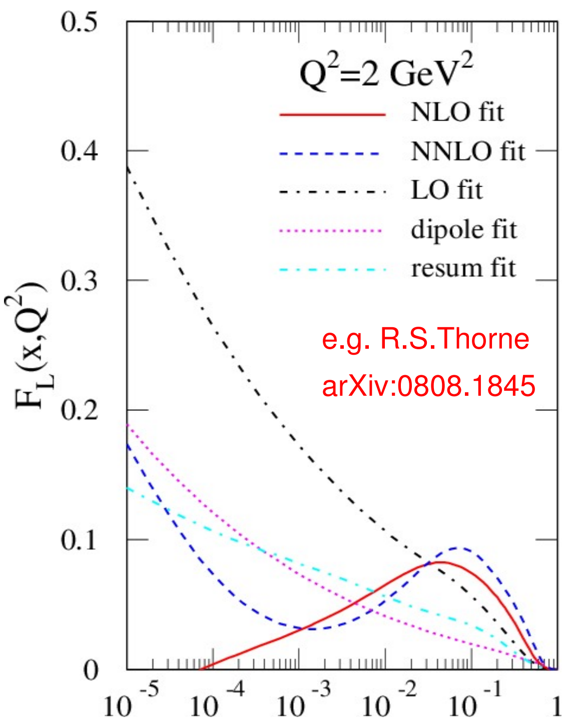
Inclusive DIS x-section depends on single scale Q^2/Q_s^2 for $x < 0.01$

(2) flat $\sigma_{diffract}/\sigma_{tot}$ vs energy



Diffract. & total x-sections similar W dependence ≠ pQCD: $\sigma_{tot}\sim W^{2\lambda} \neq \sigma_{diff}\sim W^{4\lambda}$

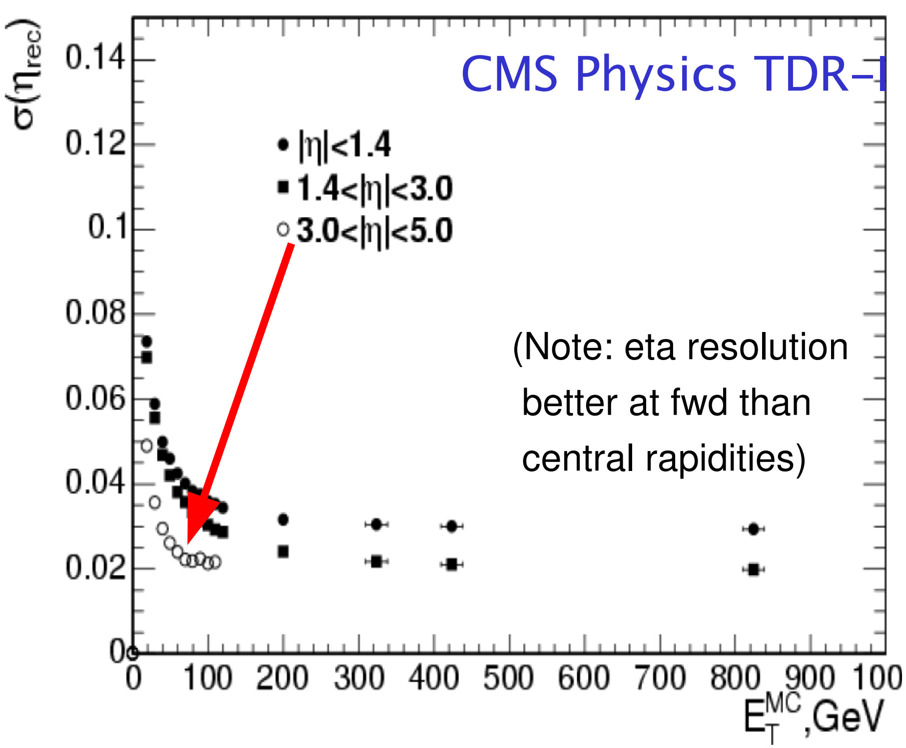
(3) Long. struc. function



Gluon (F_L) at NLO becomes negative for $Q^2 \sim 2$ GeV² at low-x

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

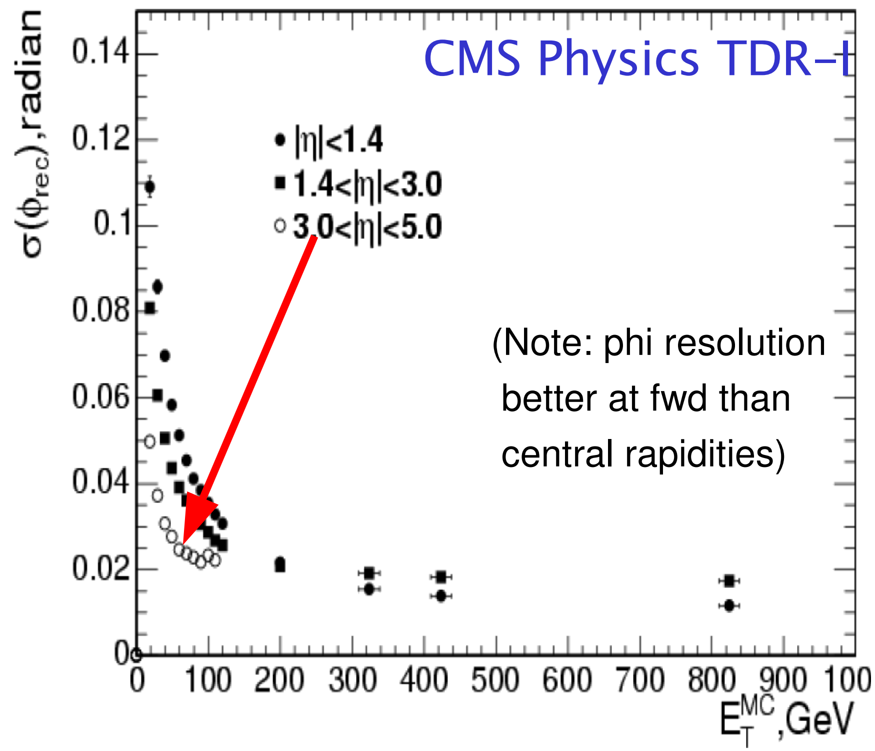
- Good η resolution



$\sim$0.05 ($p_T\sim$20 GeV)

$\sim$0.020 (p_T>100 GeV)

- Good ϕ resolution:



$\sim$0.050 rads ($p_T\sim$20 GeV),

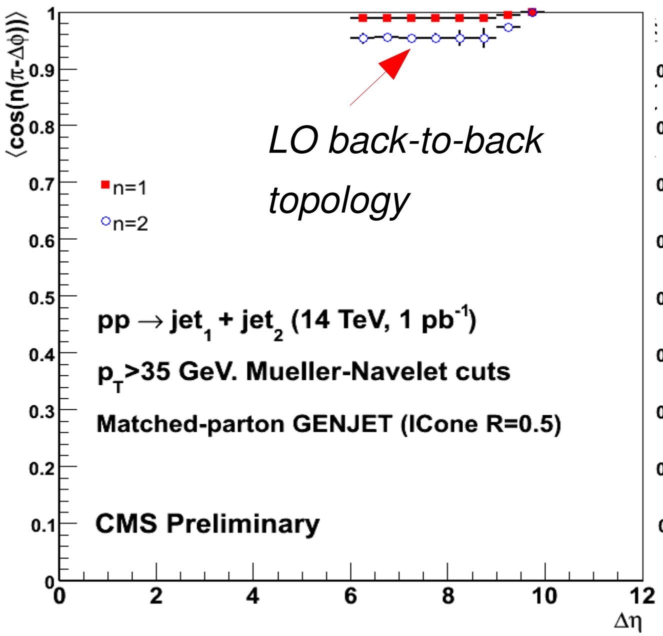
$\sim$0.020 rads (p_T>100 GeV)

- Note: resolution is better than at fwd. rapidities (boosted jet) !

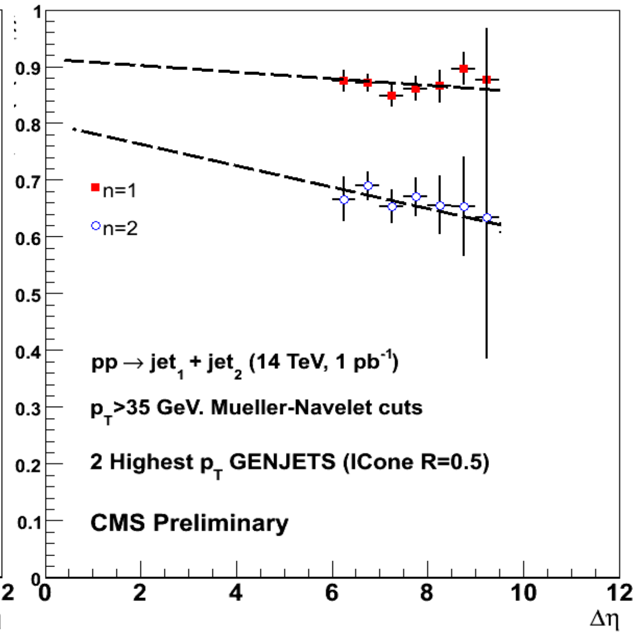
MN dijets: $\langle \cos n(\pi - \Delta\phi) \rangle$

- Average decorrelation vs. $\Delta\eta$:

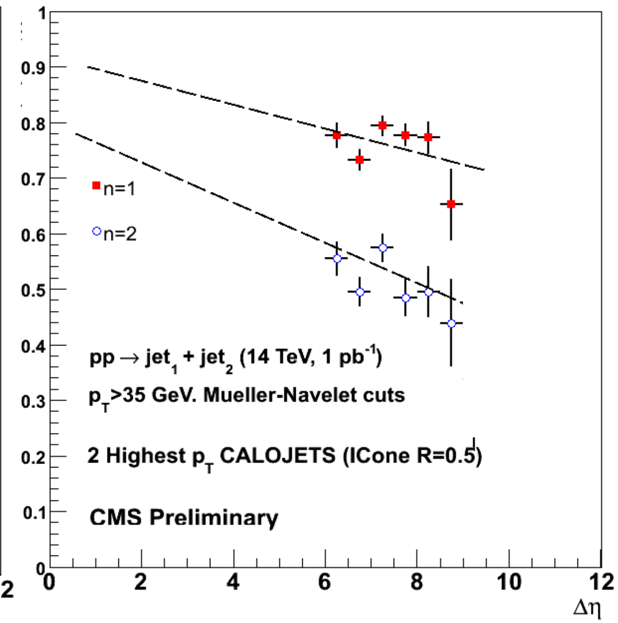
Parton-level



GenJet



CorrCaloJet



- Point-to-point errors: Statistical (dominant)
- Dijet azimuthal decorrelation (<cos(π - $\Delta\phi$)>) increased by:

  ~10-20% due parton hadronization+FS radiation effects.

  ~10-20% due experimental reconstruction effects.

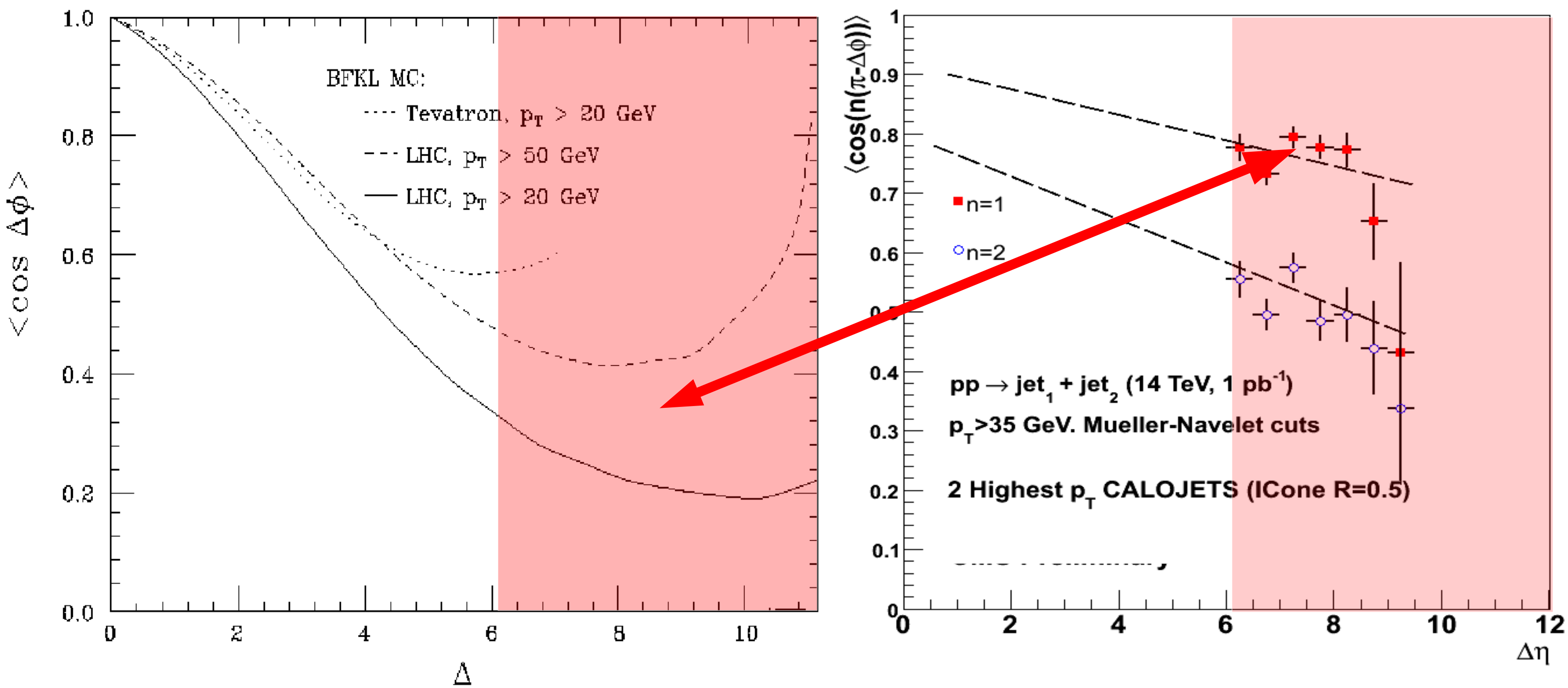
MN dijets: ⟨cos(nΔϕ)⟩ at Leading-Log

- Average cos(nΔϕ) vs. Δη: PYTHIA vs BFKL

BFKL (LL) calculations

[L.H. Orr W.J. Stirling PLB436(1998)37]

CorrCaloJet (PYTHIA)



Increasing (up to ~80%) azimuthal decorrelation with jet rapidity separation

Small (~20%) azimuthal decorrelation