Report on CERN TH Workshop

"Hard Probes in Heavy Ion Collisions at the LHC"

M. Mangano, H. Satz + U.A. Wiedemann

- 1st meeting Oct 10 – 13 2001
- 2nd meeting Mar 11 – 15 2002
- 3rd meeting Oct 7 – 11 2002
- drafting of Yellow Report
- printing 1 Aug 2003

transparencies at

http://wwwth.cern.ch/lhcworkshop/lhcworkshop01.htm

"Precursor"

Int. Journal Mod. Phys. A 10 (1995) 2881 - 3090

Contributors to Hard Processes in Hadronic Interactions

The Hard Probe Collaboration

J. Cleymans, K. Eskola, R. V. Gavai, S. Gavin, S. Gupta, D. Kharzeev, E. Quack, K. Redlich, P. V. Ruuskanen, H. Satz, G. Schuler, K. Sridhar, D. K. Srivastava, R. L. Thews, R. Vogt, X.-N. Wang

with

P. Aurenche, R. Kauffman, A. D. Martin, P. L. McGaughey, H. Plothow-Besch, G. Ridolfi, R. G. Roberts, W. J. Stirling, W. L. van Neerven

- TH only
- Aim: benchmark p-p for QGP searches
- Hard processes:
  - prompt γ's and DY
  - open charm and quarkonium
  - jets
- Extrapolation to p-A and A-B by multiplying p-p cross sections with tabulated nuclear overlap functions. $\sigma_{AB} = \sigma_{pp} \cdot AB$

goes beyond min bias

$$d\sigma_{AB} = d\sigma_{pp} \, T_{AB}(b) \, d^2b$$

[illegible] impact parameter dependent

A	R_A (fm)	z (fm)	ω	ρ_0 (fm^{-3})
16	2.608	0.513	-0.051	0.1654
27	3.07	0.519	0.	0.1739
40	3.766	0.586	-0.161	0.1699
63	4.214	0.586	0.	0.1701
110	5.33	0.535	0.	0.1577
197	6.38	0.535	0.	0.1693
208	6.624	0.549	0.	0.1600

Table 1: Nuclear shape parameters

$A+B$	$T_{AB}(0)$ (fm^{-2})	$f_{AB}=0.05$	$f_{AB}=0.1$	$f_{AB}=0.2$
16+16	7.88	12.8	25.6	51.2
16+27	11.6	21.6	43.2	86.4
16+40	14.4	32.0	64.0	128.0
16+63	18.9	50.4	100.8	201.6
16+110	24.1	88.0	176.0	352.0
16+197	32.2	157.6	315.2	630.4
16+208	31.8	166.4	332.8	665.6
27+27	17.5	36.4	72.9	145.8
27+40	22.3	54.0	108.0	216.0
27+63	30.0	85.05	170.1	340.2
27+110	39.4	148.5	297.0	594.0
27+197	53.2	265.9	531.9	1063.8
27+208	52.7	280.8	561.6	1123.2
40+40	29.2	80.0	160.0	320.0
40+63	40.5	126.0	252.0	504.0
40+110	55.3	220.0	440.0	880.0
40+197	76.4	394.0	788.0	1576.0
40+208	75.7	416.0	832.0	1664.0
63+63	57.7	198.5	396.9	793.8
63+110	81.9	346.5	693.0	1386.0
63+197	116.1	620.6	1241.1	2482.2
63+208	115.7	655.2	1310.4	2620.8
110+110	124.3	605.0	1210.0	2420.0
110+197	185.4	1083.5	2167.0	4334.0
110+208	186.4	1144.0	2288.0	4576.0
197+197	293.2	1940.4	3880.9	7761.8
197+208	298.2	2048.8	4097.6	8195.2
208+208	304.2	2163.2	4326.4	8652.8

Table 2: Values of $T_{AB}(0)$ and the central multiplicative factor for several colliding systems.

CERN TH Workshop – scope

- Limited to hard probes @LHC

  → only part of the heavy ion program @LHC

- TH + EXP knowledge transfer
- assessment of p-p benchmarks

  and p-A benchmarks

- document current TH status of medium modifications
  - identify best experimental observables
  - identify open problems
- short documentation of EXP feasibility
- specify luminosity and beam requirements and their priority:
  - Pb-Pb @ 5.5 TeV/A
  - p-A or d-A
  - lighter A-A
  - p-p @ 5.5 TeV/A

4 Working Groups – convenors

- PDFs, shadowing and p+A

  K. Eskola, W. Geist*, J.W. Qiu

- Jets

  R. Baier, O. Kodolova*, I. Lokhtin*, A. Morsch*, U.A. Wiedemann

- Heavy Flavour

  S. Frixione, D. Kharzeev, R. Vogt
  M. Bedjidian*, P. Crochet*, R. Haroutunian*, E. Vercellin*

- Photons

  P. Aurenche, P. Levai, K. Redlich, T. Peitzmann*,
  O. Kodolova*, I. Lokhtin*

- UPC

  K. Hencken, P. Yepes

p-A (d-A) Collisions @ LHC

- in principle possible
  - 2 indep. RF systems in place
  - 2 indep timing systems foreseen

- Priority?
  - currently part of LHC upgrade program
  - Lighter Ions are part of LHC Phase II

- Main issue: does p-A provide benchmark tests not available in A-A?
  - fix uncertainties in nuclear PDFs
  - test validity of factorization in pA

- p-A specific issues
  - processes with potentially large nuclear effects
  - potentially novel QCD phenomena

p-A (d-A) the machine

Table 1: Geometric cross-section, maximum centre of mass energy and rapidity shift for several collision systems.

System	σ_{tot} (barn)	$\sqrt{s}_{max}$ (TeV)	Rapidity Shift
pO	0.39	9.9	0.35
pAr	0.72	9.4	0.40
pPb	1.92	8.8	0.47
dO	0.66	7.0	0.00
dAr	1.10	6.6	0.05
dPb	2.58	6.2	0.12
αO	0.76	7.0	0.00
αAr	1.22	6.6	0.05
αPb	2.75	6.2	0.12

$$\sqrt{s} = 14\,TeV \sqrt{\frac{Z_1 Z_2}{A_1 A_2}}$$

$$y_{cent} = \frac{1}{2} \ln \frac{Z_1 A_2}{Z_2 A_1}$$

System	Luminosity $cm^{-2}s^{-1}$	N_p 10^{10}	N_{ion} 10^{10}	N_{ion}^{max} 10^{10}
pPb	$1.1 \cdot 10^{29}$	1.4	0.004	0.007
pAr	$3.0 \cdot 10^{29}$	3.7	0.004	0.055
pO	$5.5 \cdot 10^{29}$	6.7	0.004	0.1

nuclear modifications of PDFs

The comparison Irrespective of whether the best fit is found automatically or by eye, the basic procedure to determine the nPDF in the EKRS and HKM analyses is the same. The results obtained for the nuclear effects are, however, quite different, as can be seen in the comparison at $Q^2 = 2.25$ GeV^2 shown in Fig. 5. The main reason for this is that different data sets are used:

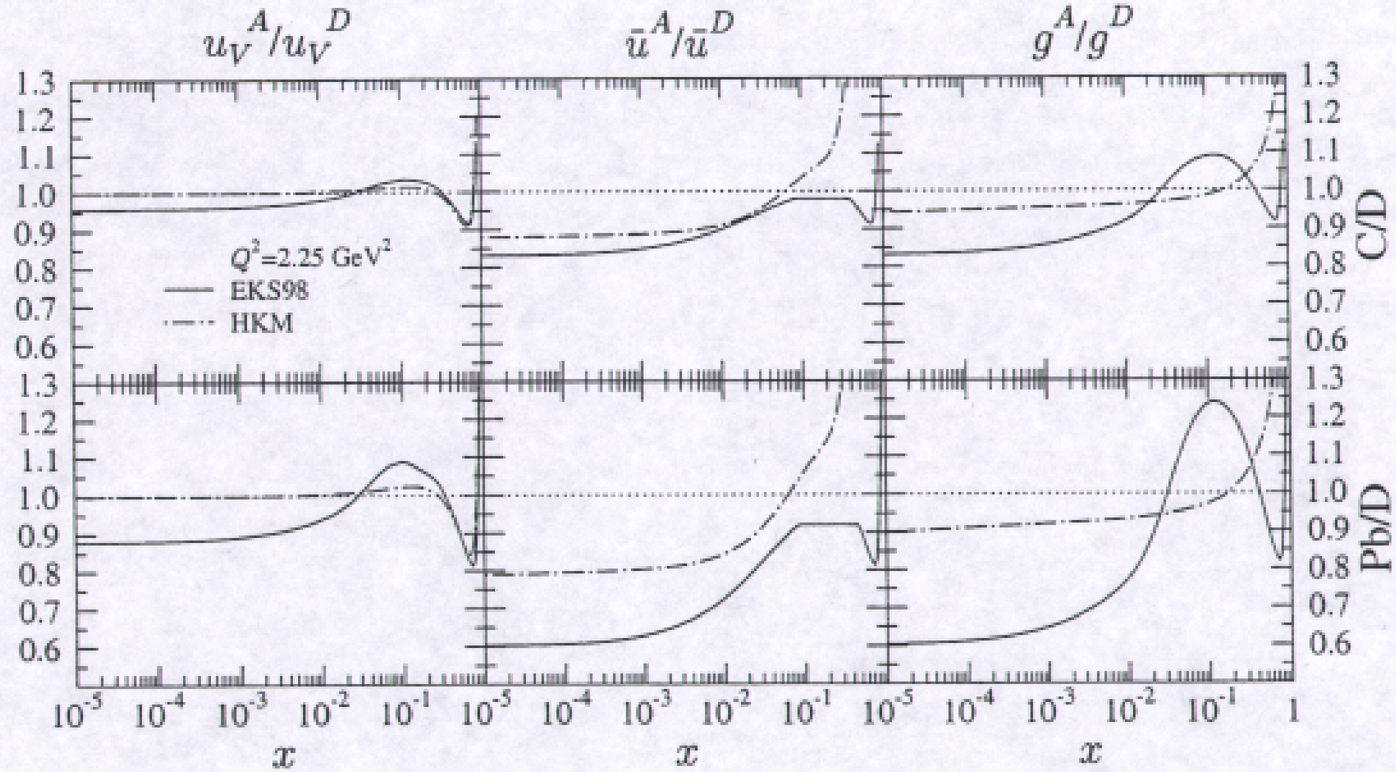
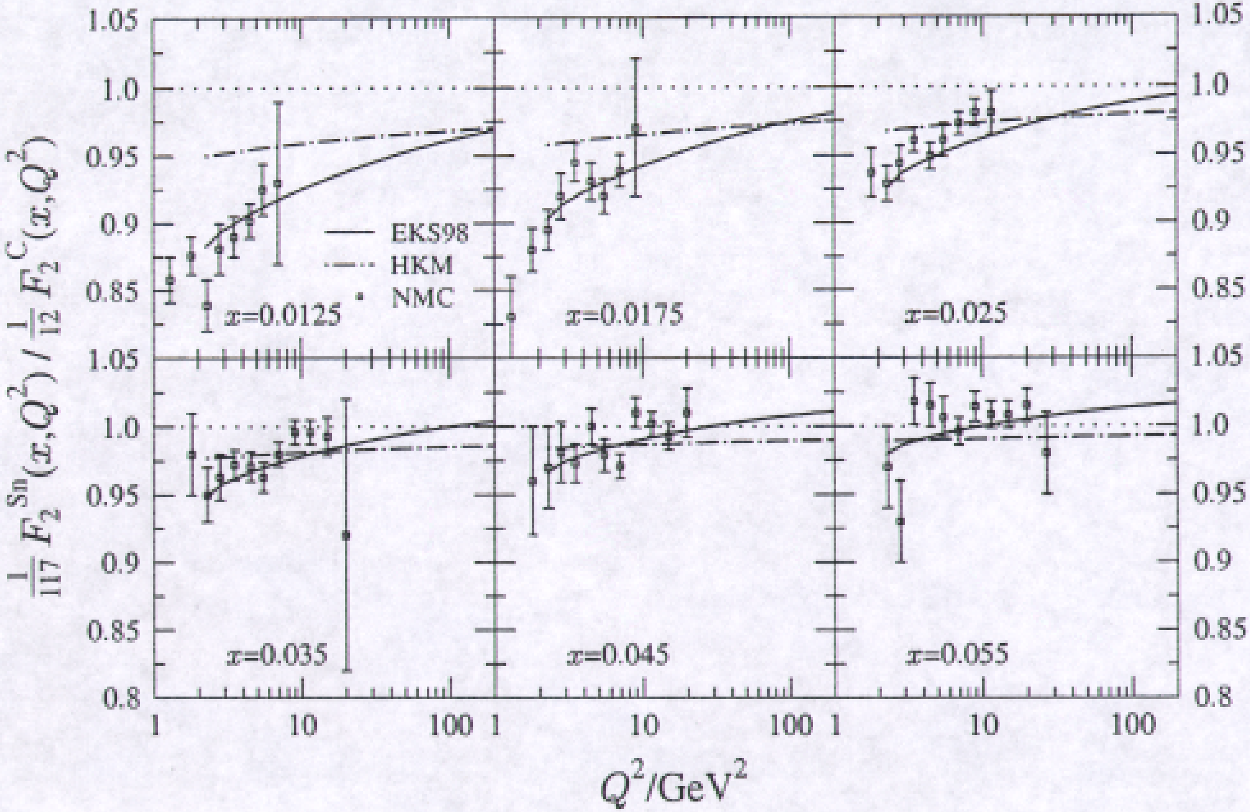
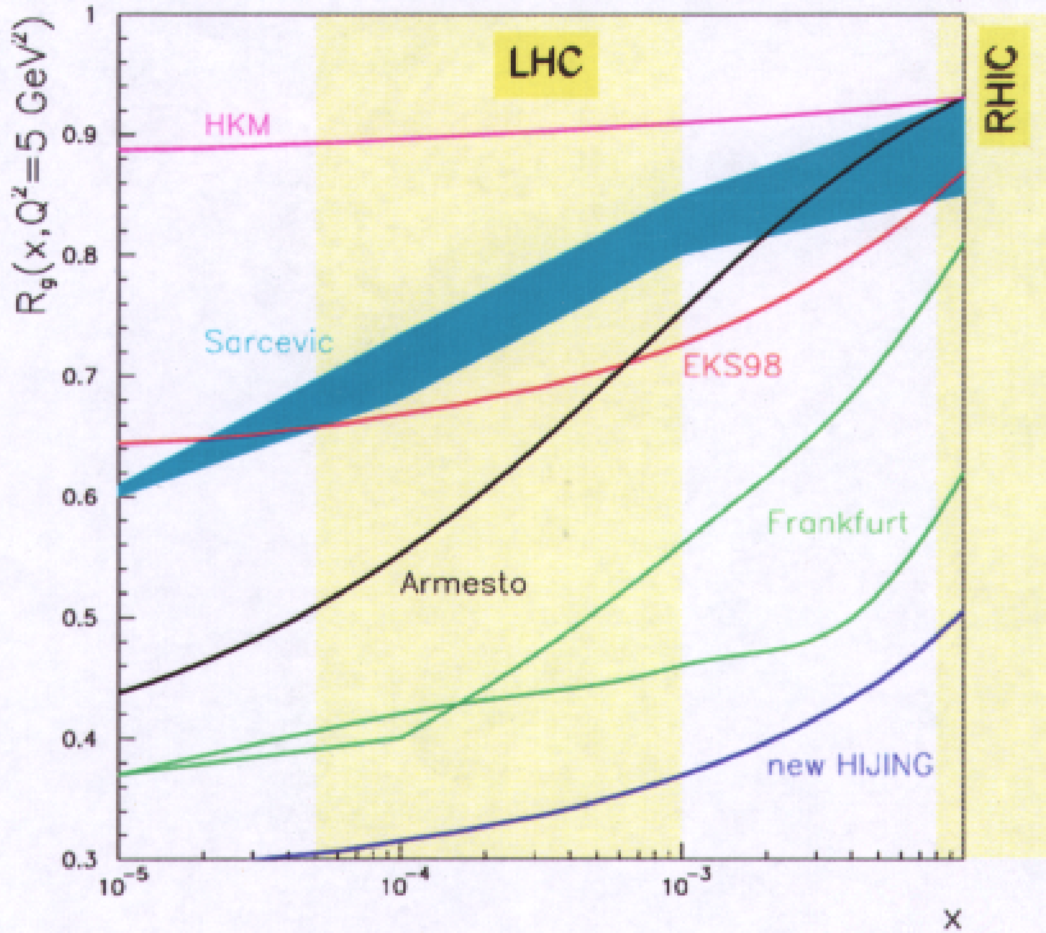


Fig. 5: The nuclear modifications for the u_V, $\bar{u}$ and gluon distributions in EKS98 (solid) and in HKM (dotted dashed) at $Q^2 = 2.25$ GeV^2. Upper panels: C/D. Lower panels: Pb/D, with isoscalar Pb.



uncertainties in nPDFs can be narrowed partly
by comparing to existing data

Uncertainties in nuclear gluon distribution



How to narrow this?

Semi-leptonic decays of correlated $D\bar{D}$

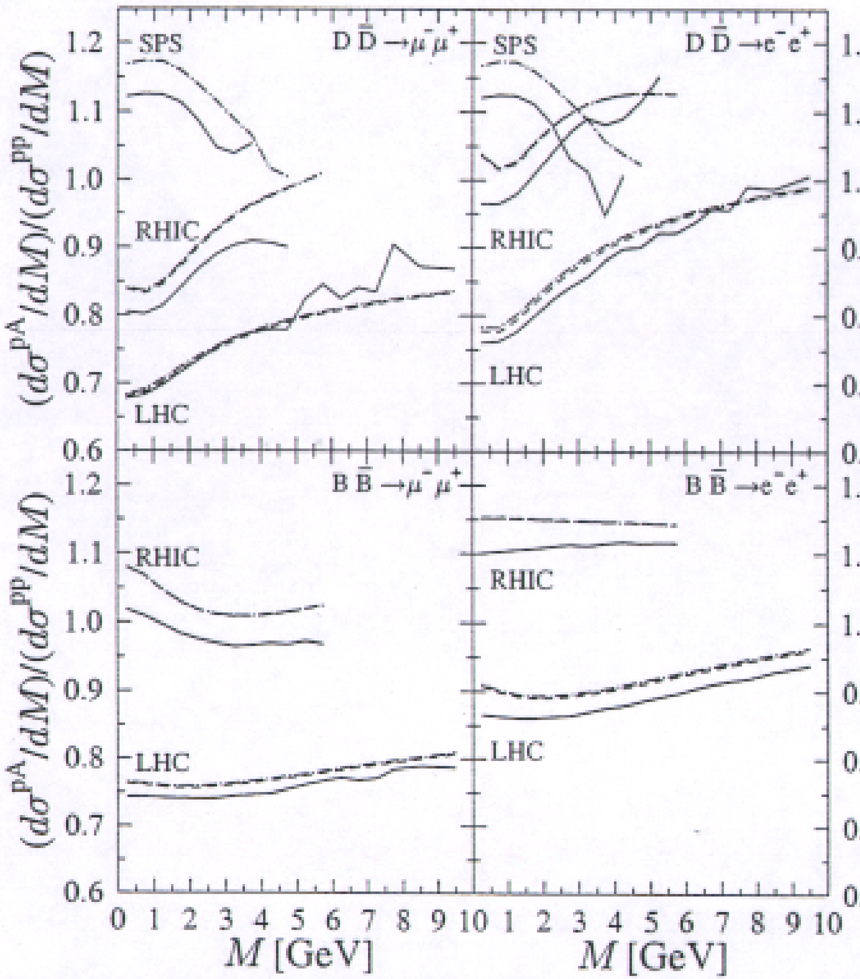
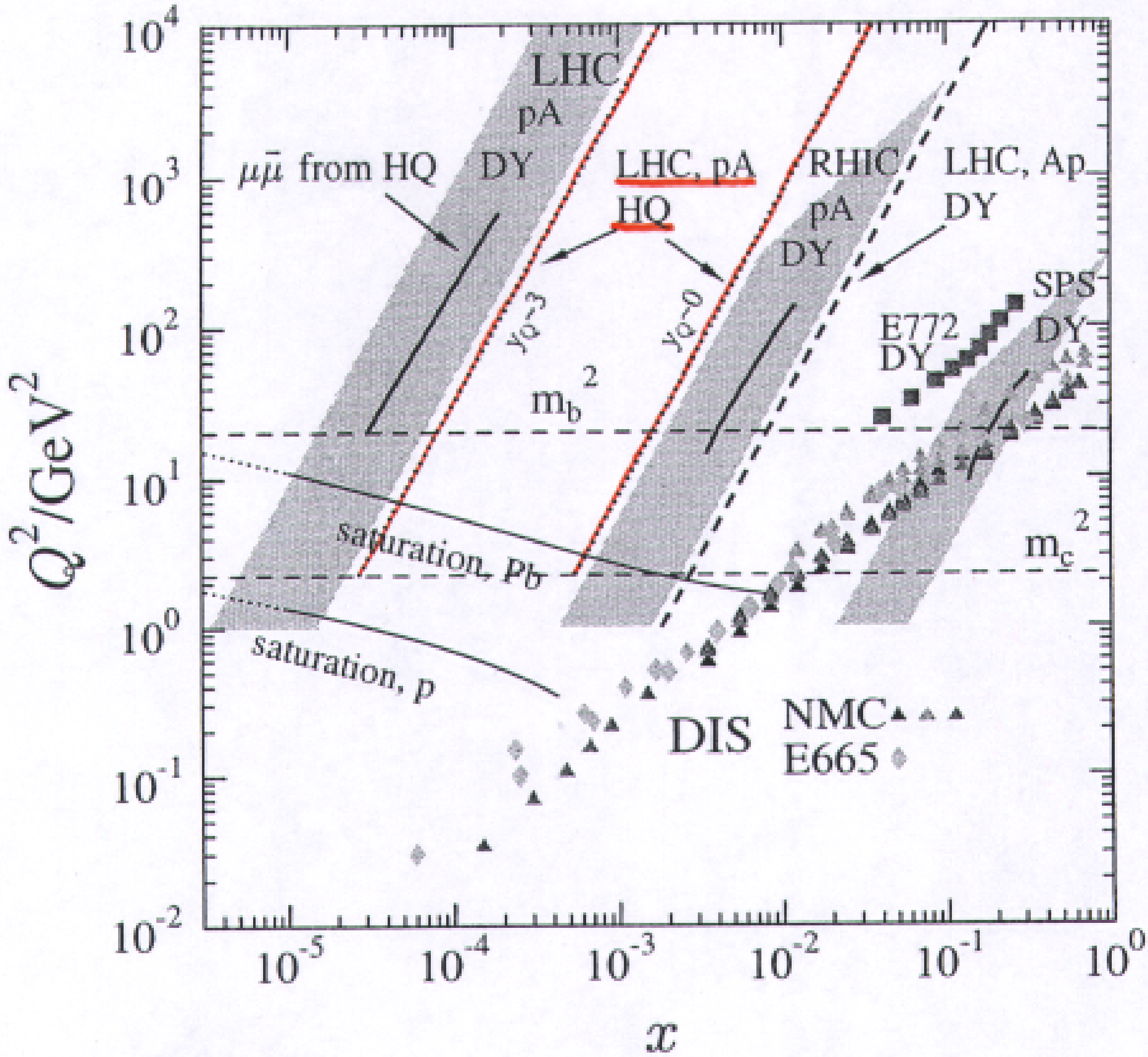


Fig. 42: The ratios of lepton pairs from correlated $D\overline{D}$ and $B\overline{B}$ decays in pA to pp collisions at the same energies (solid curves) compared to the input R_g^A at the average x_2 and Q (dashed)/$\sqrt{\langle Q^2 \rangle}$ (dot-dashed) of each M bin. From Ref. [45].

Hard Probes testing gluc in p+A

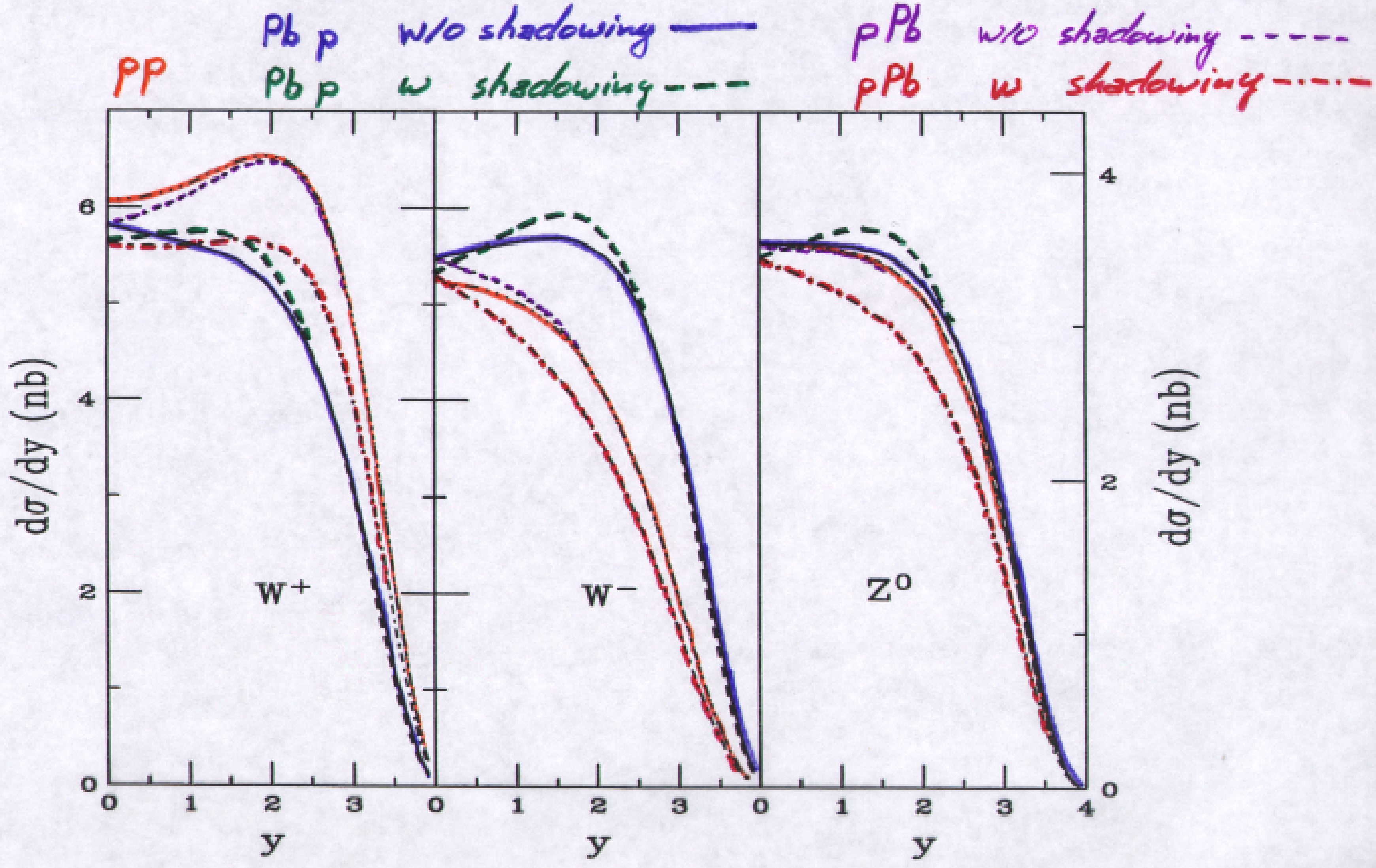
e.g. $$\left.\frac{\sigma_{pA}^{D\bar{D}}}{\sigma_{pp}^{D\bar{D}}}\right|_{2.5<y<4} \simeq \frac{f_g^A}{f_g^p}$$



Benchmark W, Z

Isospin versus shadowing

Anti-shadowing   shadowing



Jet Production @ LHC

- hugh rates
  - benchmark p-p
  - benchmark p-A

- possible large nuclear effects – QGP-signatures
  - suppression of jet $E_\perp$-spectra
    → FSeffect tested via dijet momentum imbalance, impact parameter dependence, ...

  - modification of internal jet structure
    → suppression of leading hadrons
      - medium-modified fragmentation functions
      - hierarchy of expected suppression

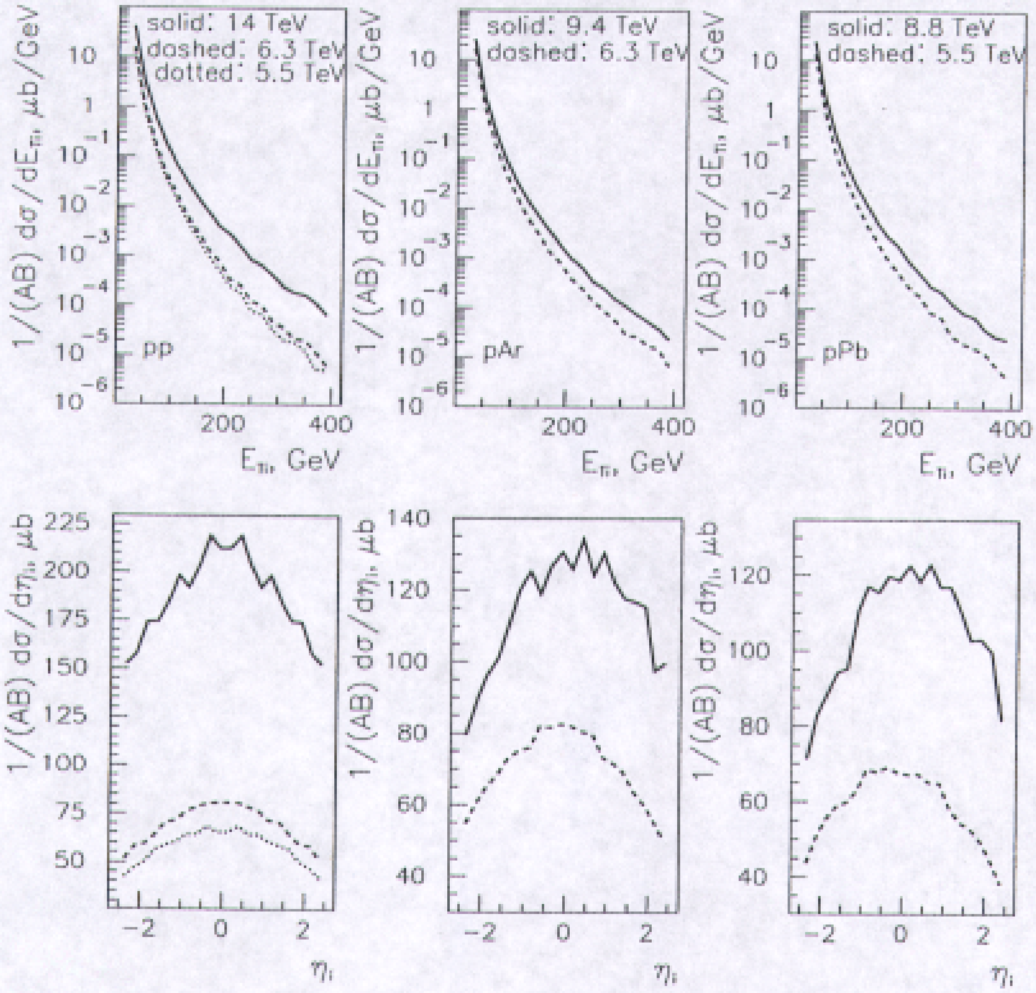
    → modified jet shapes
      - $p_\perp$ - broadening of jet cone
      - changes in jet multiplicity, ...

W,Z cross sections per nucleon

Table 5: Gauge boson cross sections per nucleon. No decay channel is specified.

Δy	σ_{NS} (nb)	σ_{EKS98} (nb)	σ_{NS} (nb)	σ_{EKS98} (nb)	σ_{NS} (nb)	σ_{EKS98} (nb)
	Z^0		W^+		W^-	
			pp 5.5 TeV			
$y < 2.4$	8.10	-	15.13	-	11.41	-
$y < 1$	3.51	-	6.13	-	5.16	-
$2.4 < y < 4$	2.01	-	5.68	-	2.42	-
			Pb*p* 5.5 TeV			
$y < 2.4$	8.23	8.37	13.12	13.34	13.37	13.63
$y < 1$	3.53	3.53	5.71	5.67	5.56	5.54
$2.4 < y < 4$	2.14	2.06	3.72	3.62	4.36	4.24
			*p*Pb 5.5 TeV			
$y < 2.4$	8.12	7.39	14.87	13.43	11.62	10.57
$y < 1$	3.52	3.33	5.95	5.60	5.31	5.01
$2.4 < y < 4$	2.01	1.68	5.67	4.69	2.43	2.02
			Pb*p* 8.8 TeV			
$y < 2.4$	12.37	12.47	19.62	19.71	19.87	20.01
$y < 1$	5.22	5.11	8.37	8.16	8.22	8.02
$2.4 < y < 4$	5.07	5.03	8.30	8.31	9.46	9.47
			*p*Pb 8.8 TeV			
$y < 2.4$	12.26	10.93	21.41	18.96	18.08	16.09
$y < 1$	5.20	4.82	8.60	7.92	7.98	7.35
$2.4 < y < 4$	4.83	3.95	11.80	9.58	5.98	4.87

pA jet cross section $\sqrt{s}$-dependence



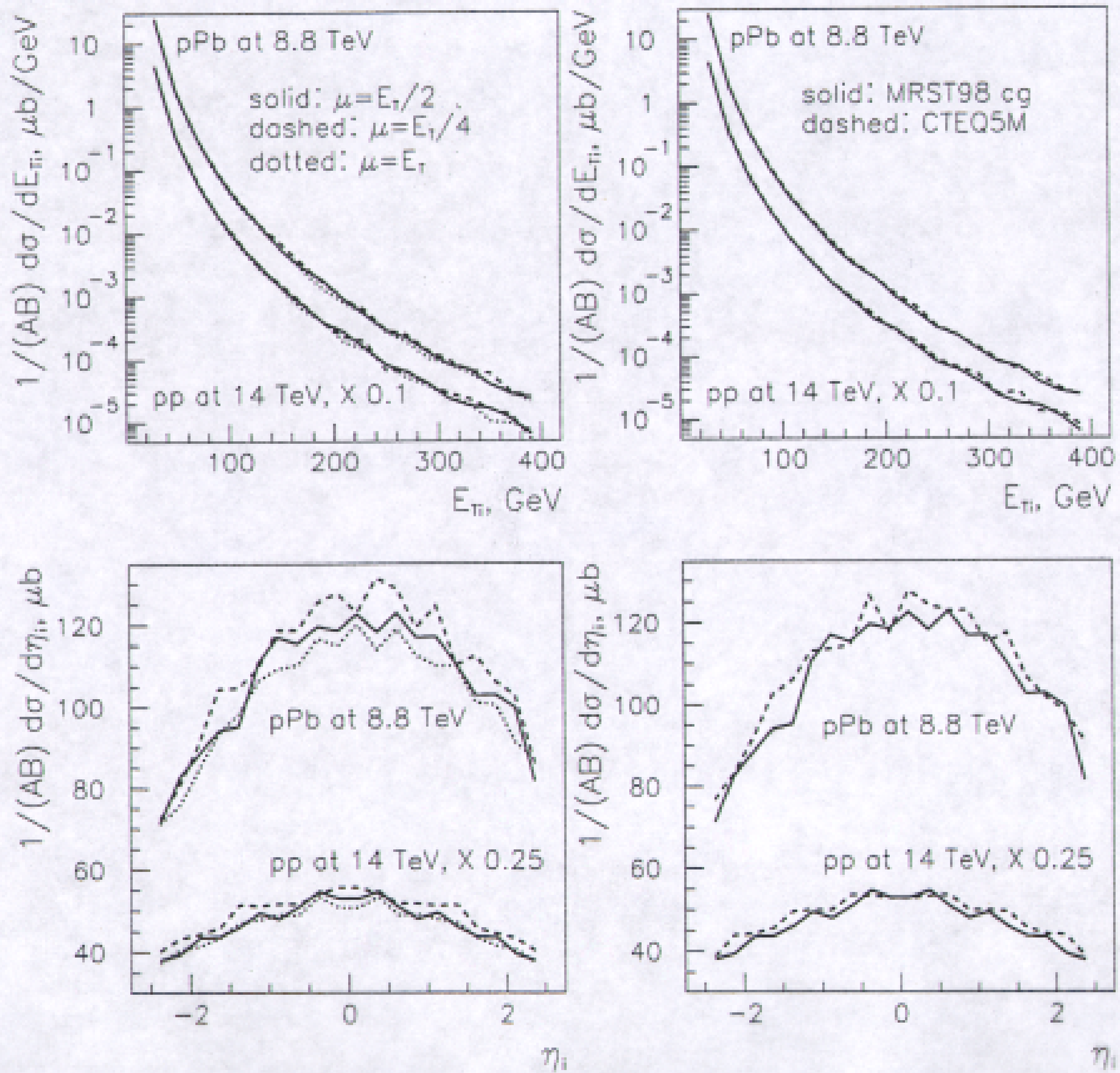
$|\eta_i| < 2.5$

for $E_T > 20$ GeV

	$\mathcal{L}$ ($cm^{-2}s^{-1}$)	# Ev per month per μb/AB
PP	10^{34}	10^{10}
pPb	10^{29}	2×10^{7}
PbPb	5×10^{26}	2×10^{7}

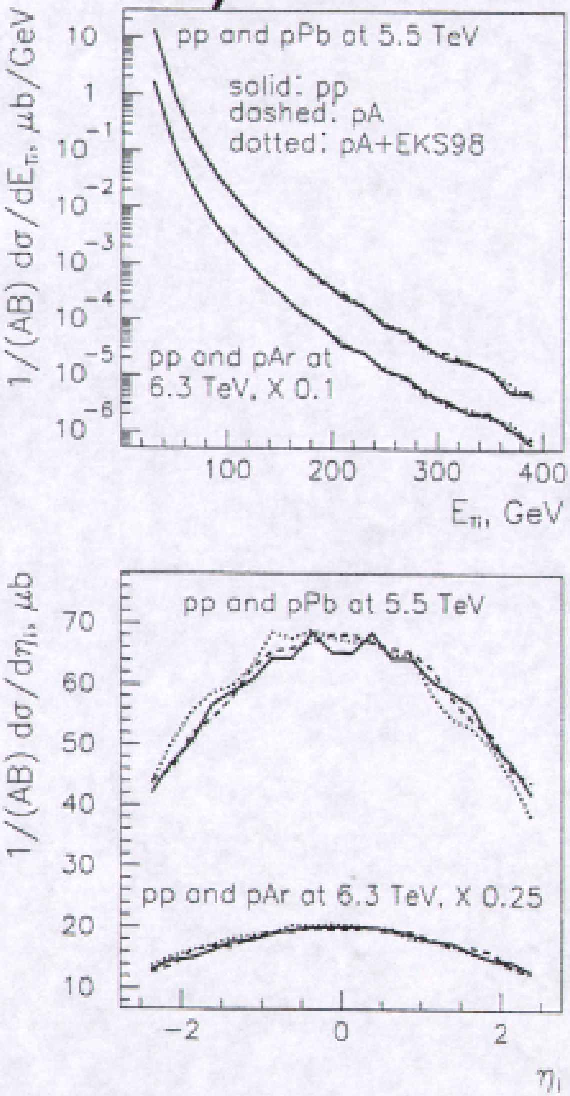
NLO-Jet cross section: p-A benchmark

weak dependence on scale and pdf

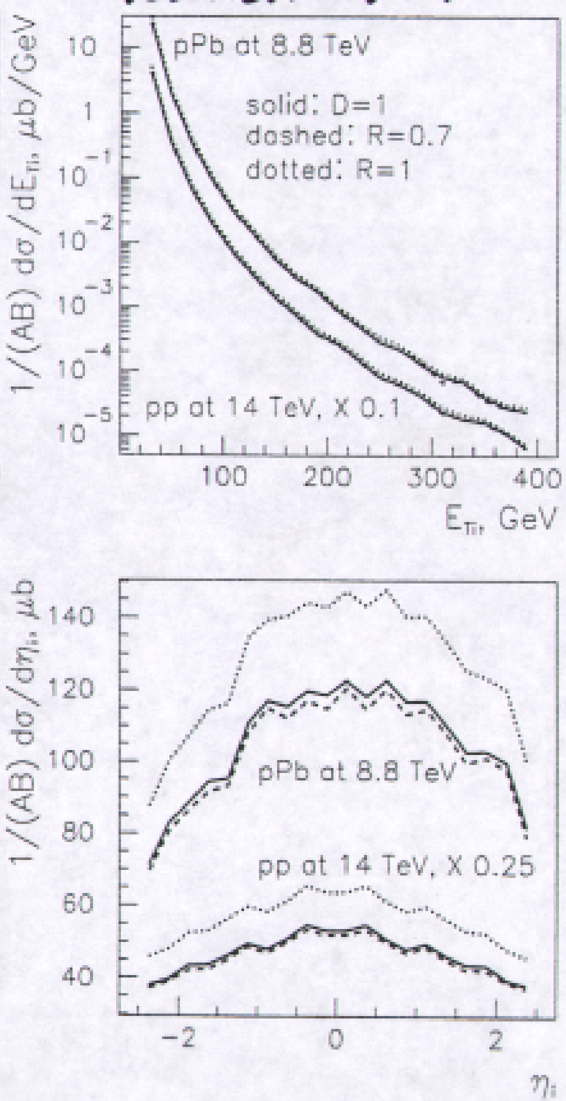


NLO Jet cross section for pA

weak dependence on isospin and nPDF

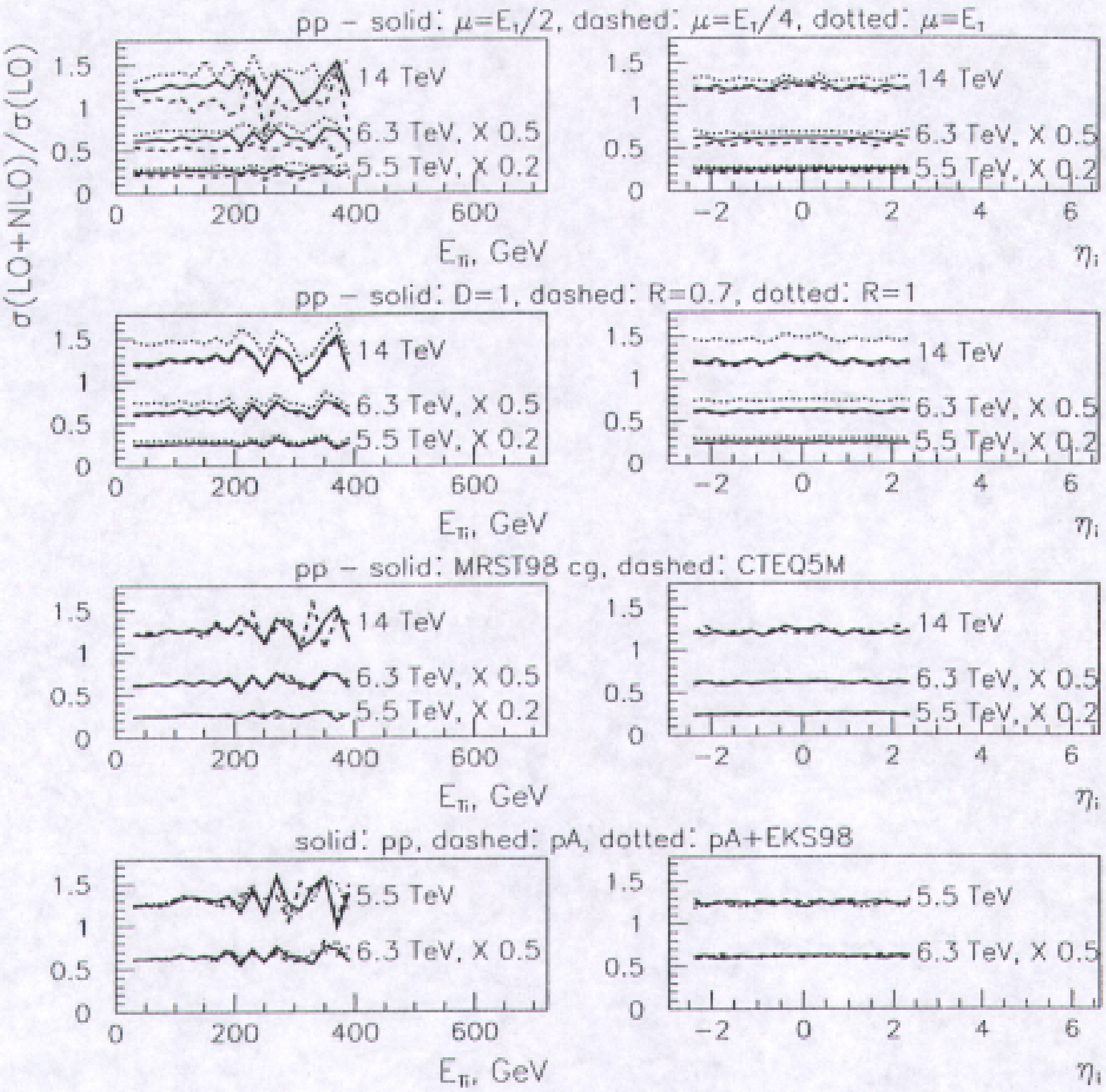


dependence on jet reconstruction



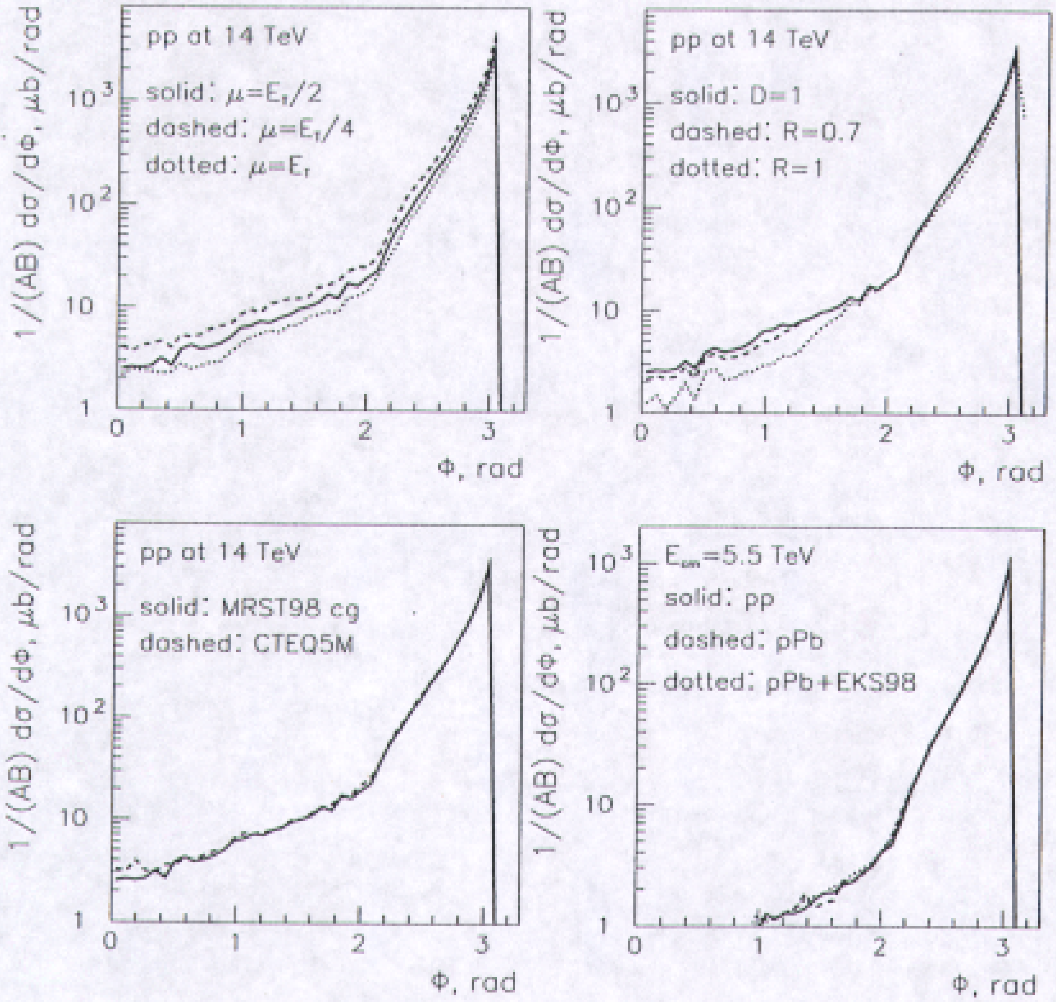
Jet cross section K-factor

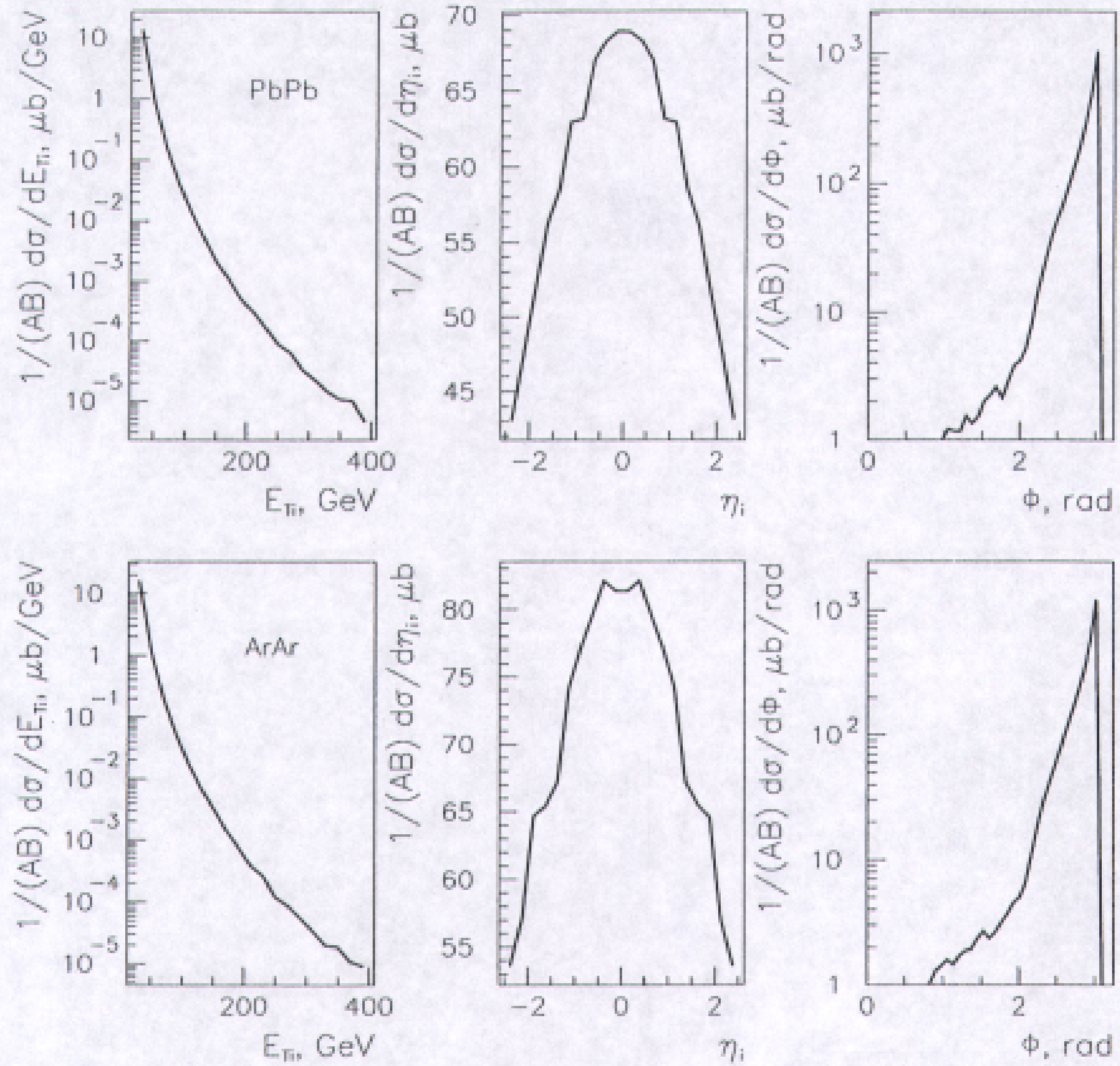
$K \simeq 1.2 - 1.3$



Uncertainties in dijet cross sections

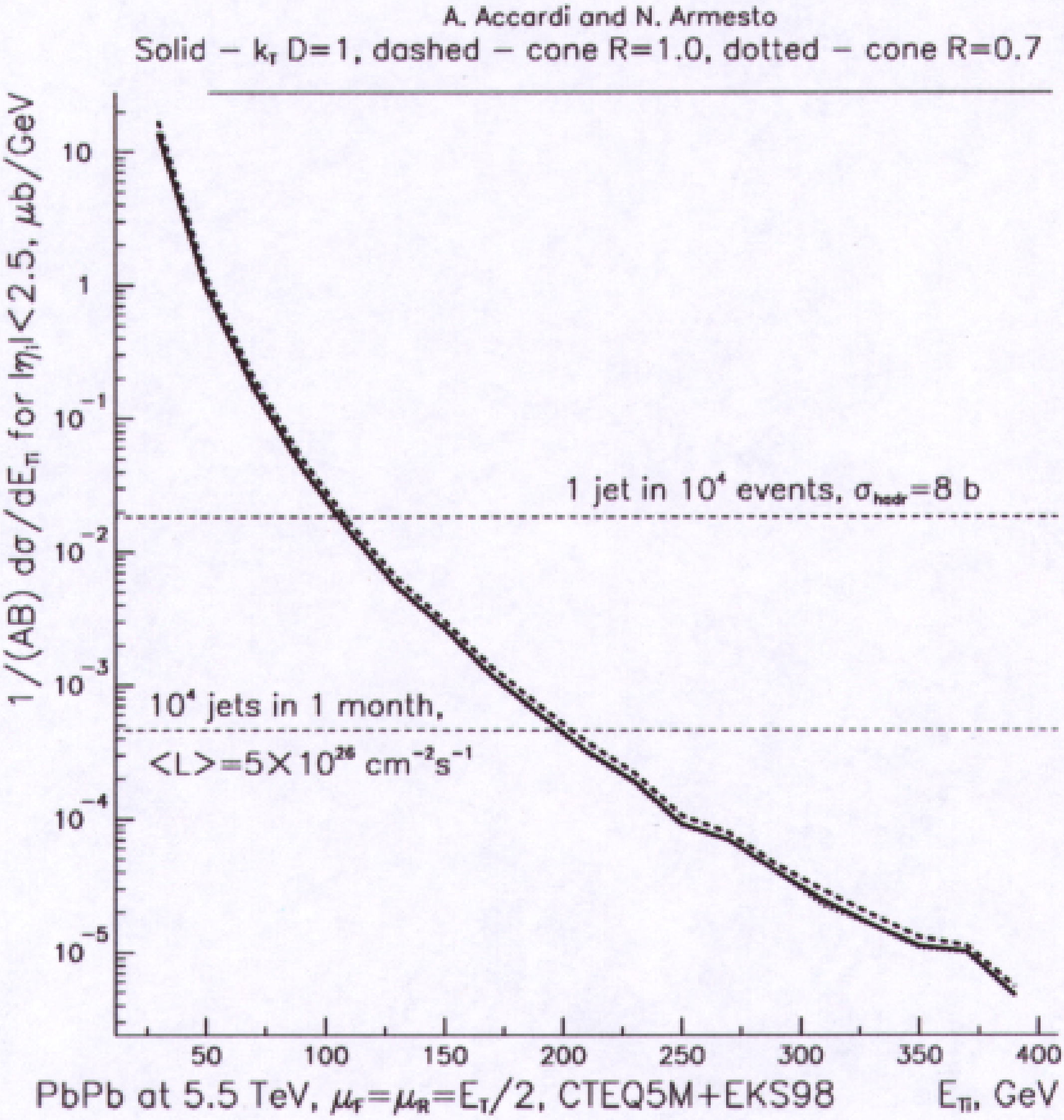
$E_{T_1} > 20$ GeV $\quad E_{T_2} > 15$ GeV , $\quad |y_i| < 2.5$



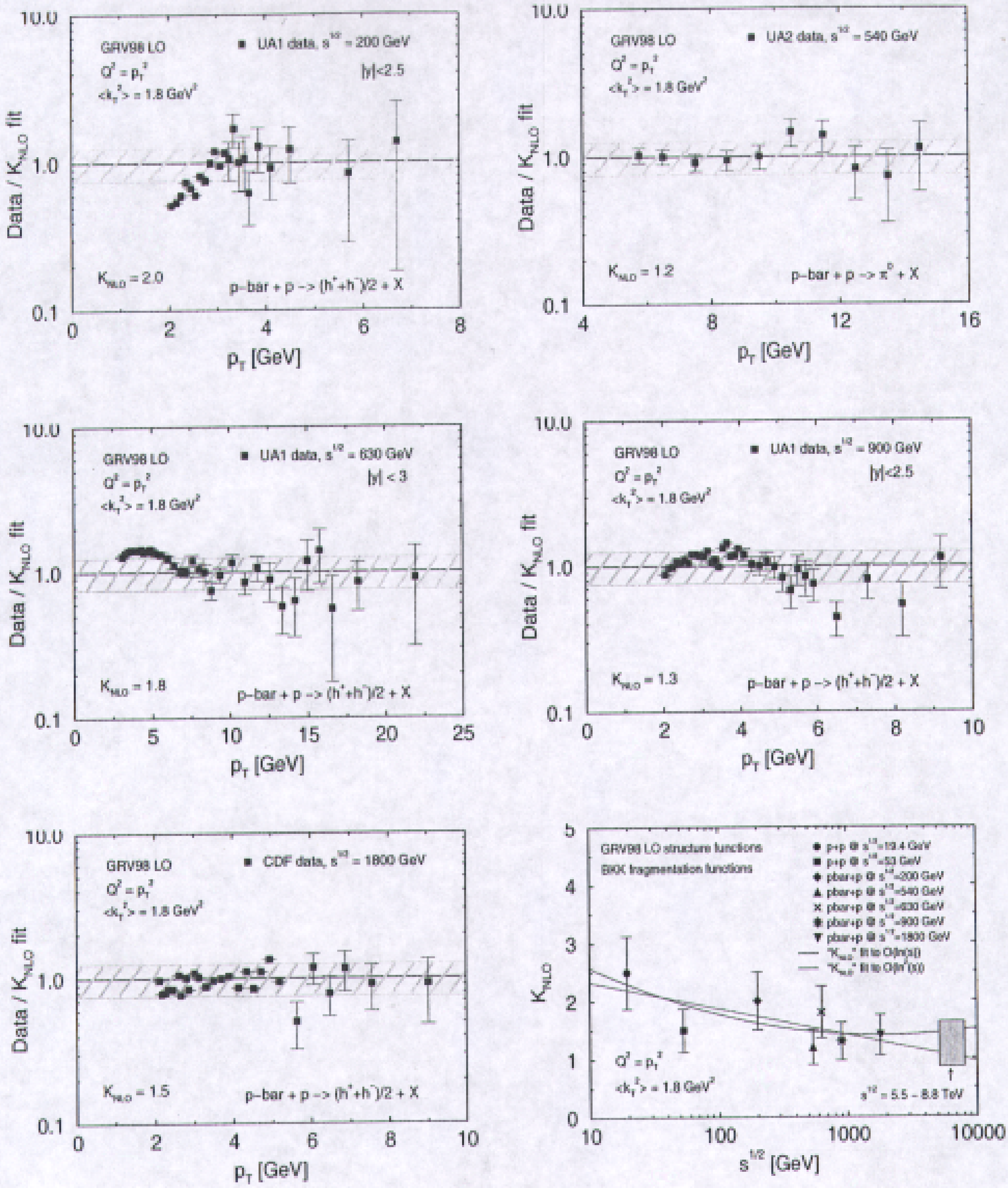

PbPb
ArAr
1/(AB) dσ/dE_Ti, μb/GeV
E_Ti, GeV
1/(AB) dσ/dη_i, μb
η_i
1/(AB) dσ/dφ, μb/rad
φ, rad

Jet production at LHC, Pb+Pb

sufficient statistics after one month of running at design luminosity

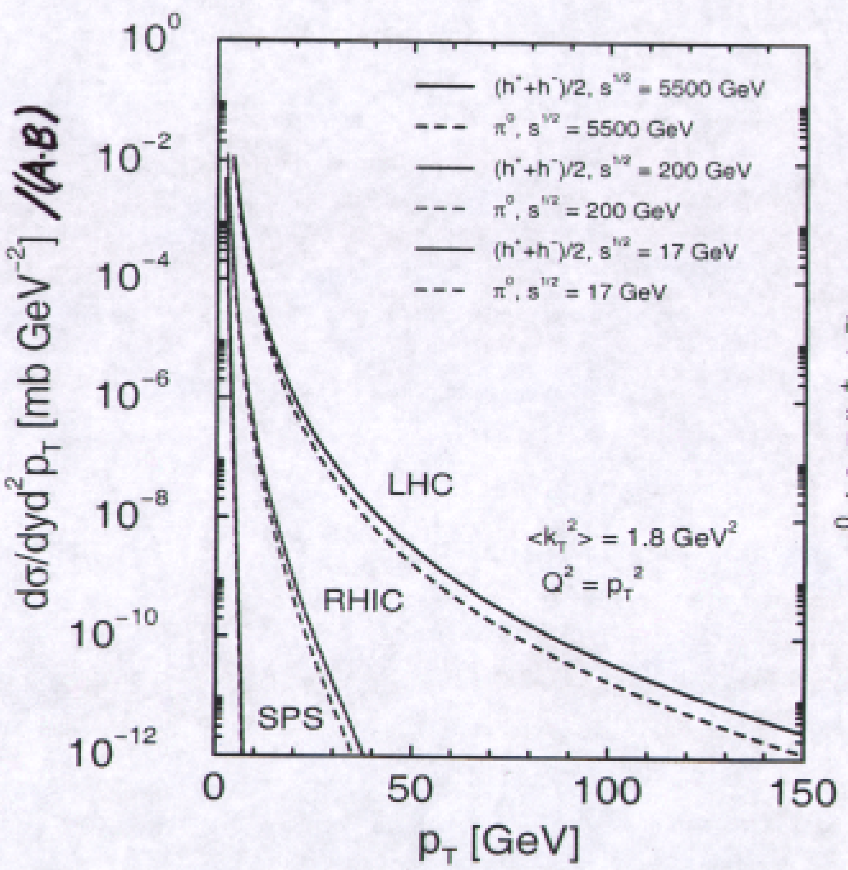


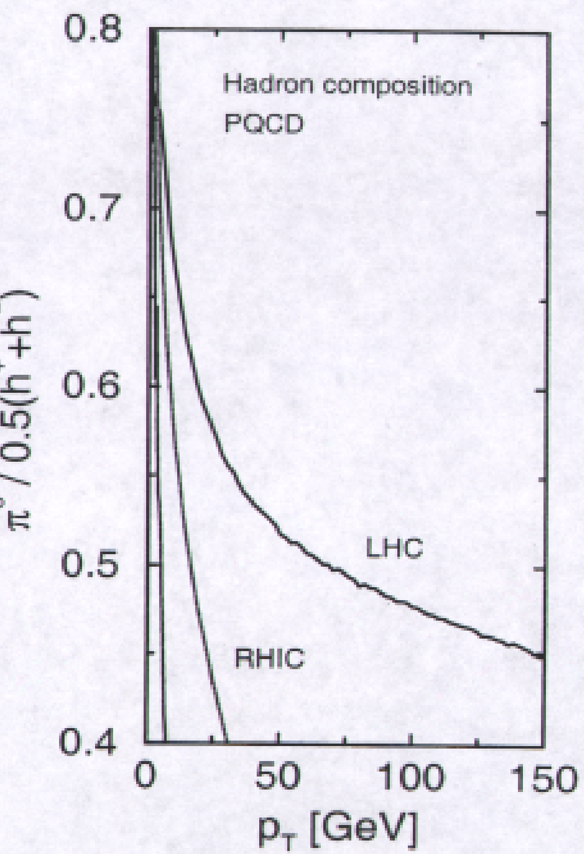
Leading hadron spectra



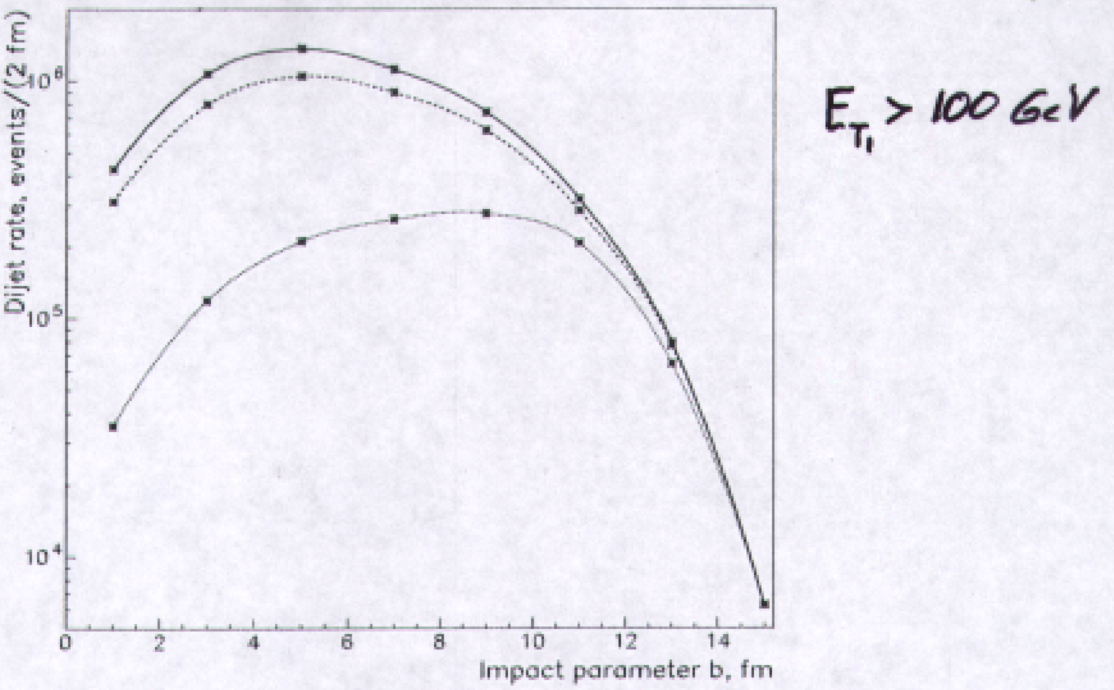
this study: LO + $\langle k_t^2 \rangle$ + K-factor

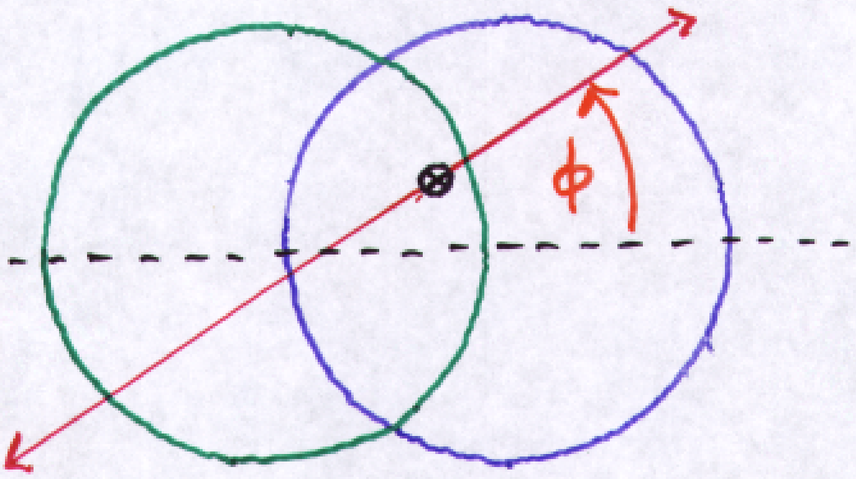
Leading hadron spectra

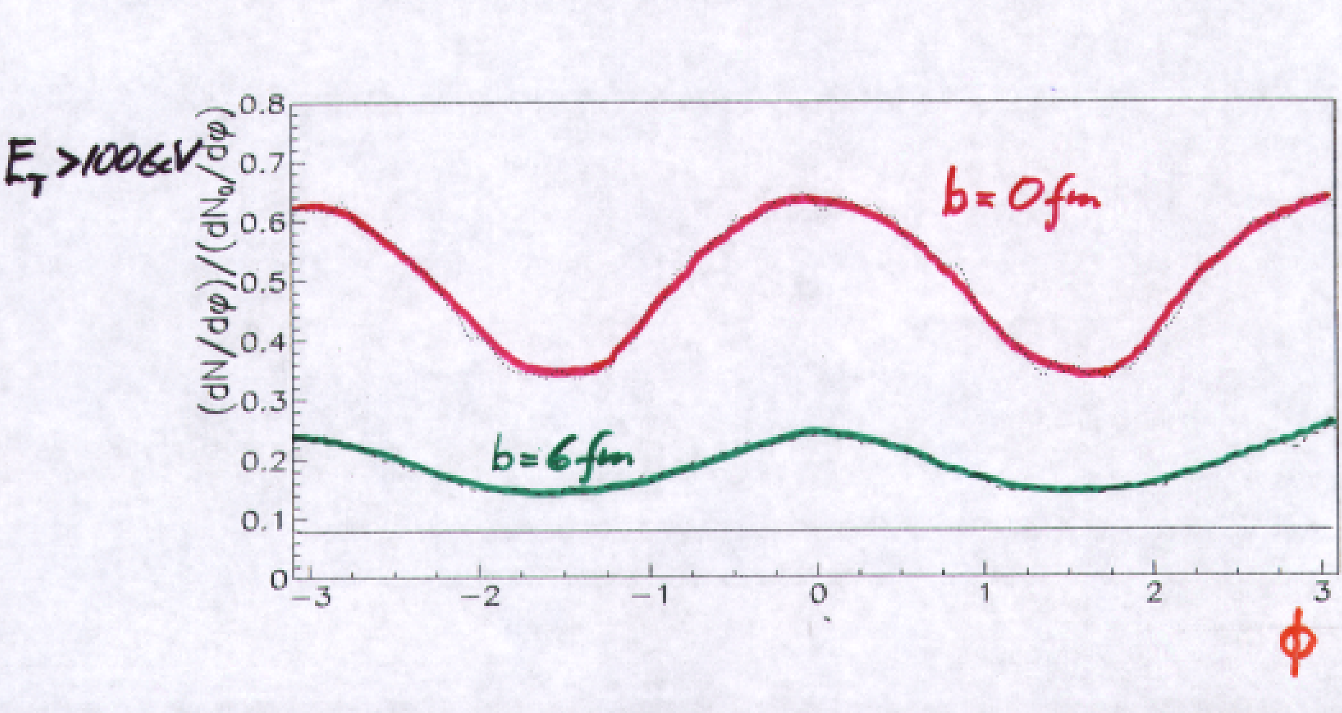




"Model" studies: Pb-Pb nuclear geometry

- 

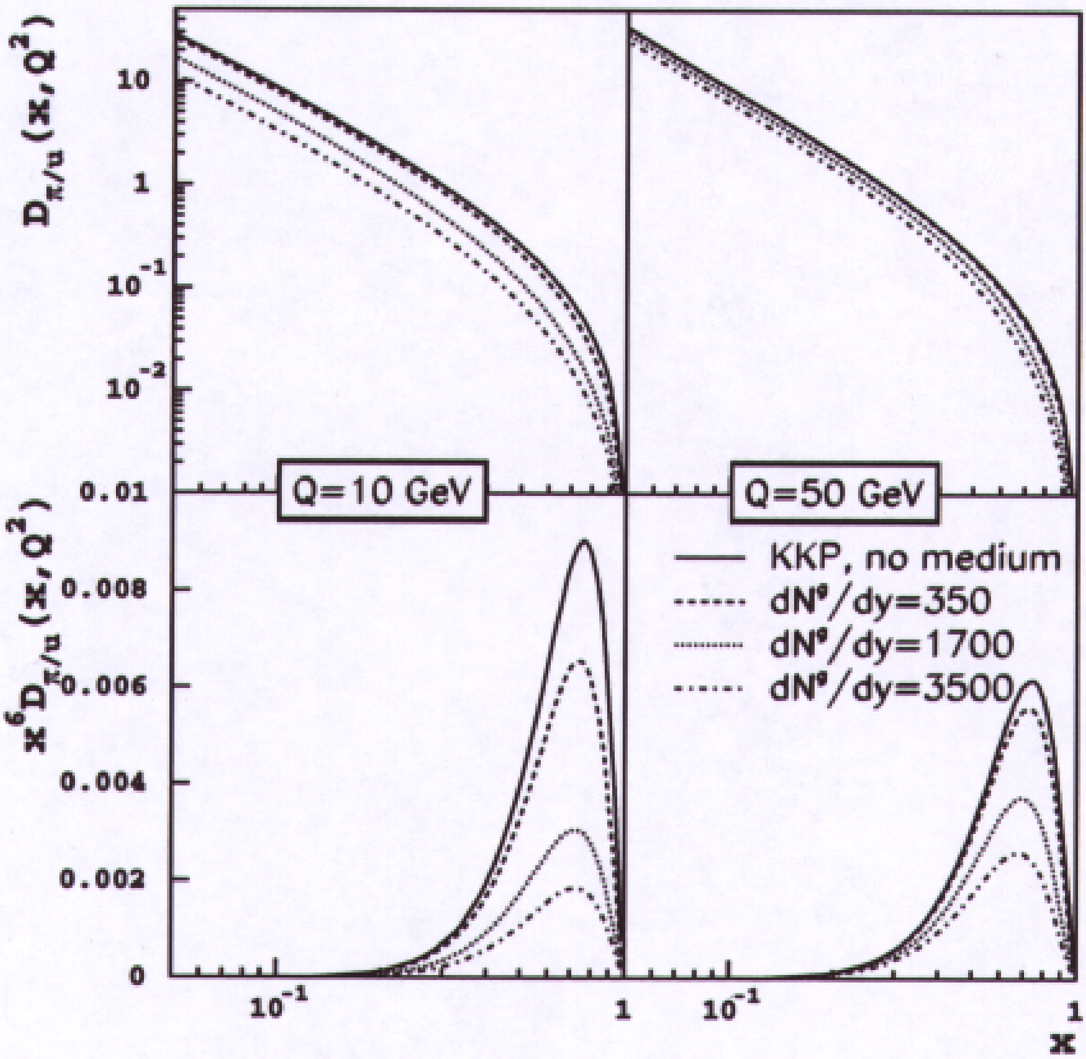
- 



Medium-modified fragmentation

$R = \omega_c L = \frac{L^2}{R_A^2} \frac{dN^g}{dy}$, measures density

If particle multiplicity is increased by factor 5, then then same medium-modification shows up at ~ 5 higher $p_\perp$.
$\Longrightarrow$ Medium effects in perturbative window @ LHC.



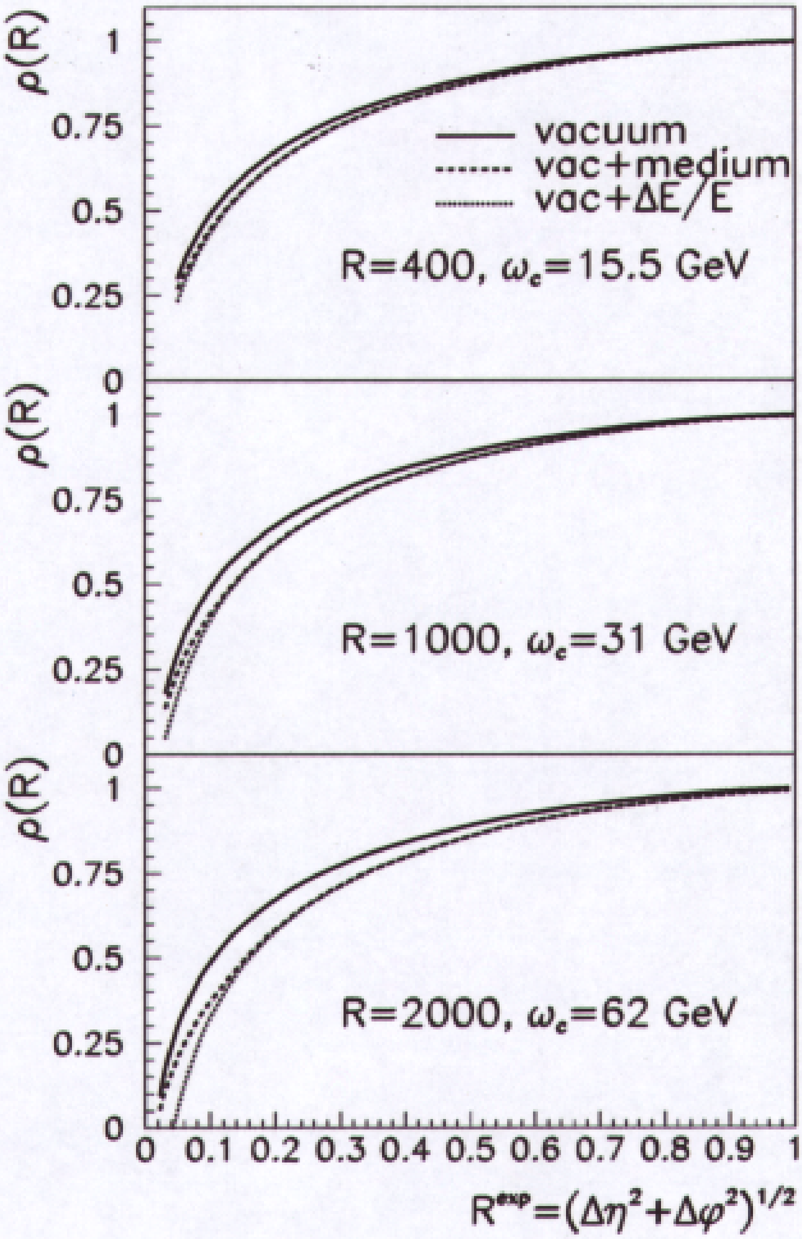
C.A. Salgado + U.A. Wiedemann, Phys. Rev. Lett. 89:092303,2002

Medium-modified jet shapes

$$\rho(r) = \frac{1}{N_{\text{jets}}} \sum_{\text{jets}} \frac{E_\perp(r)}{E_\perp(r=1)}\Bigg|_{r \equiv \sqrt{(\Delta\eta)^2+(\Delta\Phi)^2}} .$$

U.A. Wiedemann, Nucl. Phys. A690, 731 (2001)

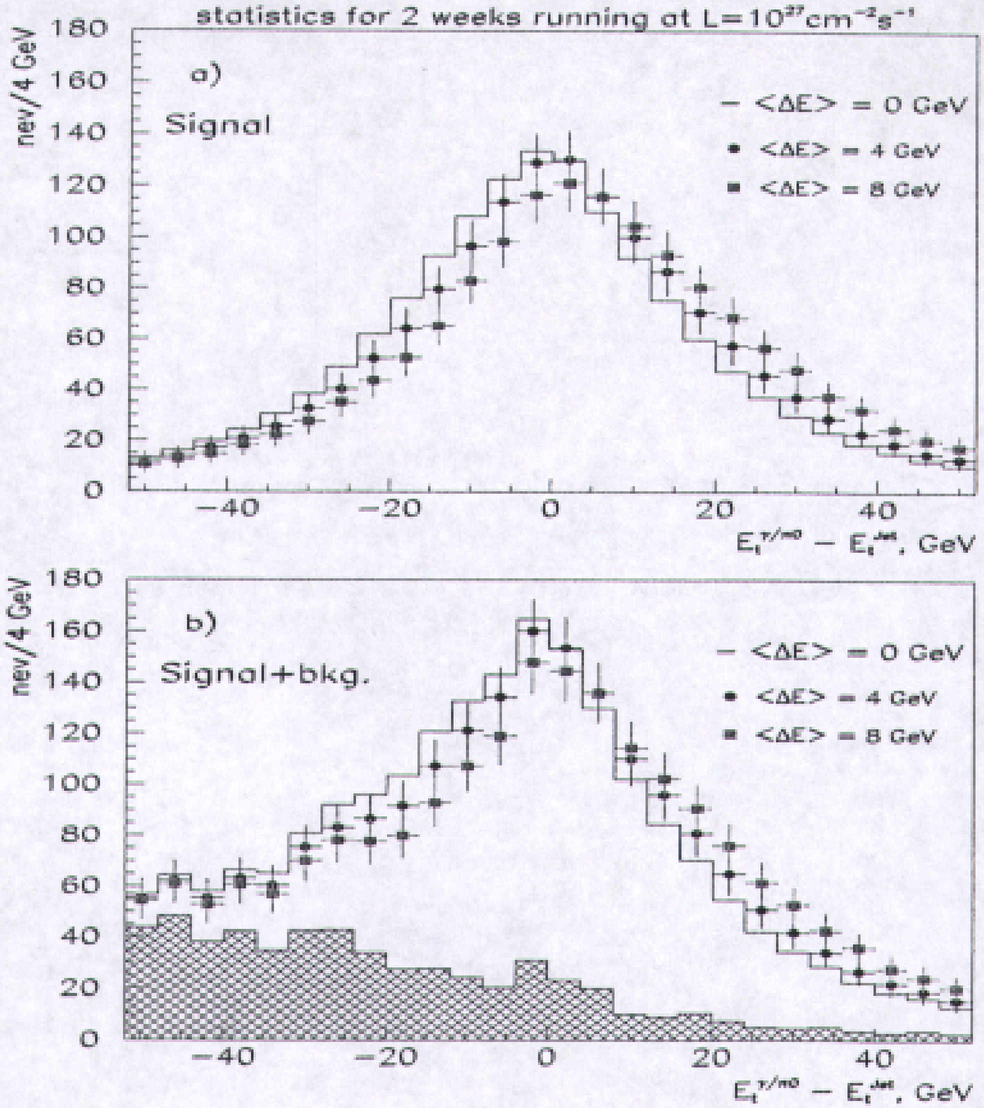
C. Salgado, U.A. Wiedemann, in preparation (2003)



~~γ - jet~~

$E_T^\gamma > 120$ GeV

$|\eta_\gamma| < 1.5$



Prompt photon production in pp

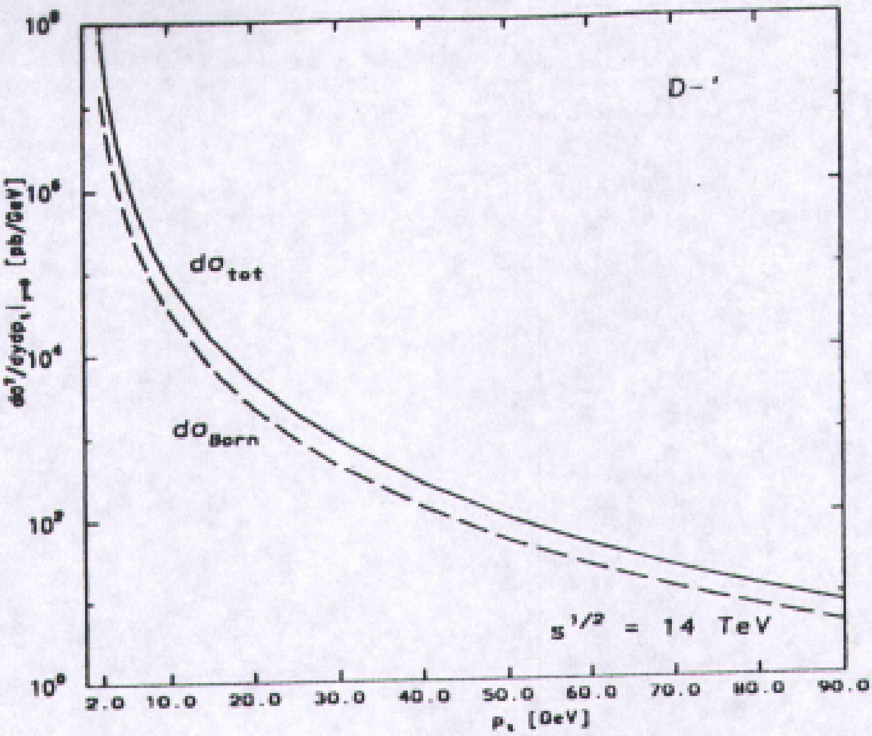
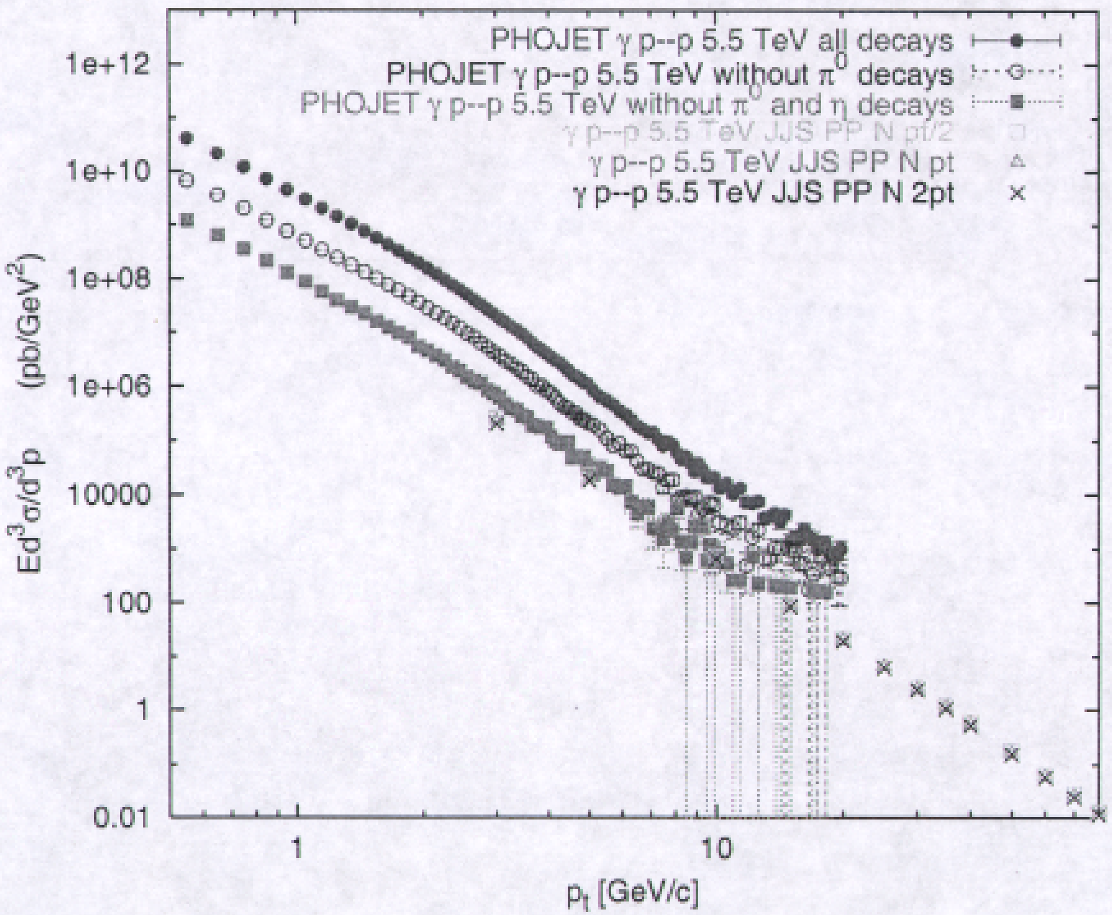


Figure 13a

Photons: prompt γ vs. π^0-, η-decays



Heavy Flavour

- hugh rates – benchmark issues
  - Large K-factor, $\sqrt{s}$-dependence
  - quarkonium – formation

- Large nuclear effects – QGP signatures
  - heavy quark energy loss
    → e.g. D/π ratio at high $p_\perp$
  - charmonium suppression
  - bottomonium suppression

Charm total rates in p-p

$$(I) \quad : \quad m_c = 1.5 \text{ GeV}, \quad \mu_R = m_c, \quad \mu_F = 2m_c$$
$$(II) \quad : \quad m_c = 1.2 \text{ GeV}, \quad \mu_R = m_c, \quad \mu_F = 2m_c$$
$$(III) \quad : \quad m_c = 1.8 \text{ GeV}, \quad \mu_R = m_c, \quad \mu_F = 2m_c$$
$$(IV) \quad : \quad m_c = 1.5 \text{ GeV}, \quad \mu_R = 2m_c, \quad \mu_F = 2m_c$$

$\sqrt{S} = 14$ TeV:

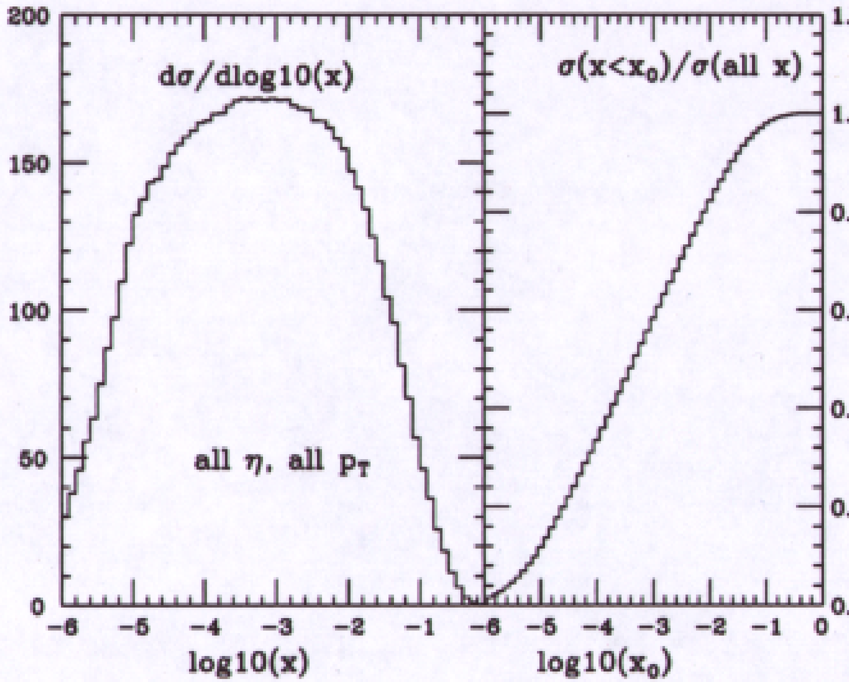
param	σ(mb)	K factor (σ_{NLO}/σ_{LO})
(I)	15.2	2.9
(II)	26.7	3.4
(III)	9.4	2.6
(IV)	7.4	2.8

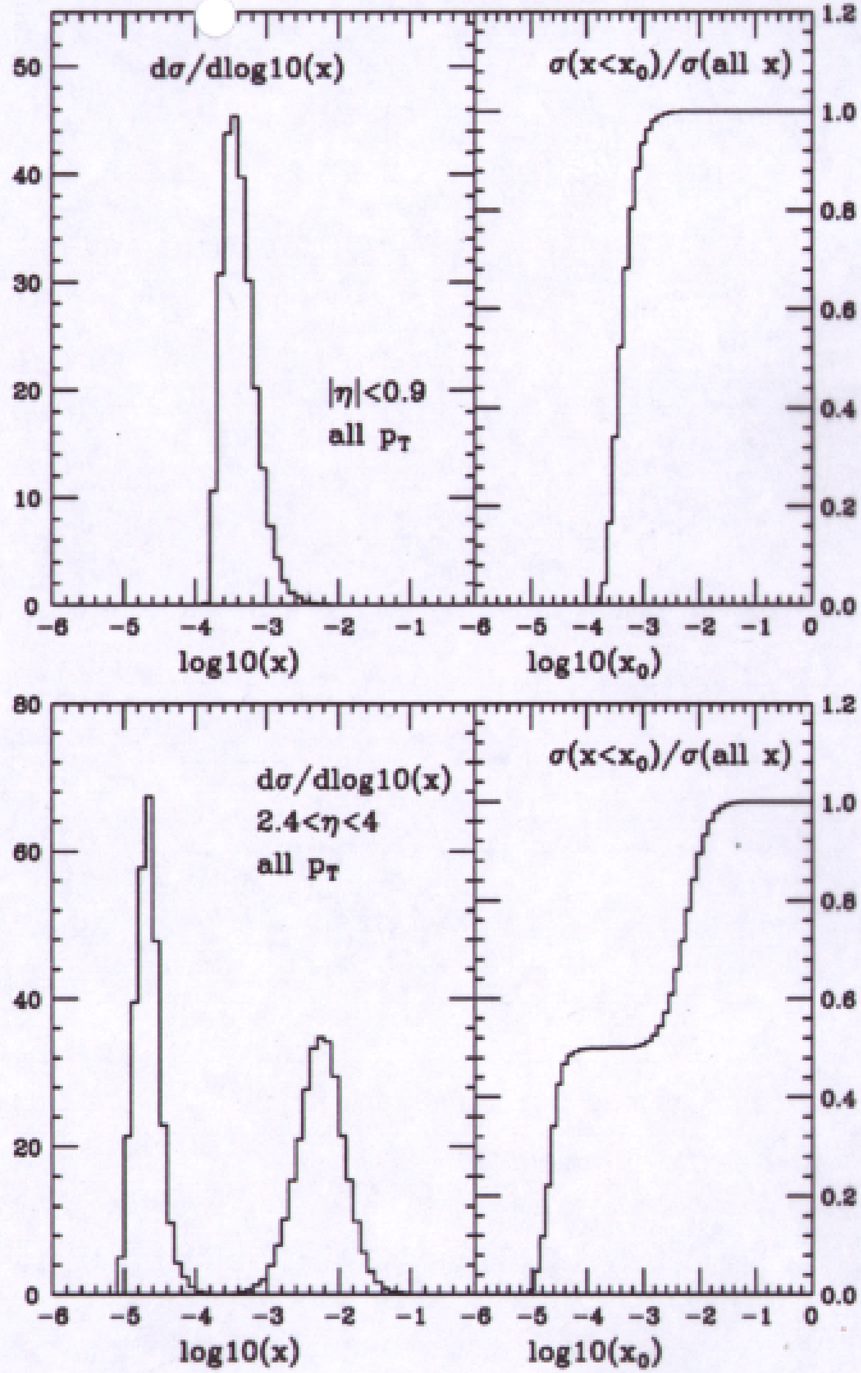
$\sqrt{S} = 5.5$ TeV:

param (Π)	σ(mb)	$R(\Pi) = \sigma_{5.5}/\sigma_{14}$	$R(\Pi)/R(\Pi = \mathrm{I})$
(I)	8.0	0.53	1.
(II)	14.9	0.56	1.06
(III)	4.7	0.50	0.95
(IV)	4.0	0.53	1.02

PDF dependence $\lesssim 5\%$

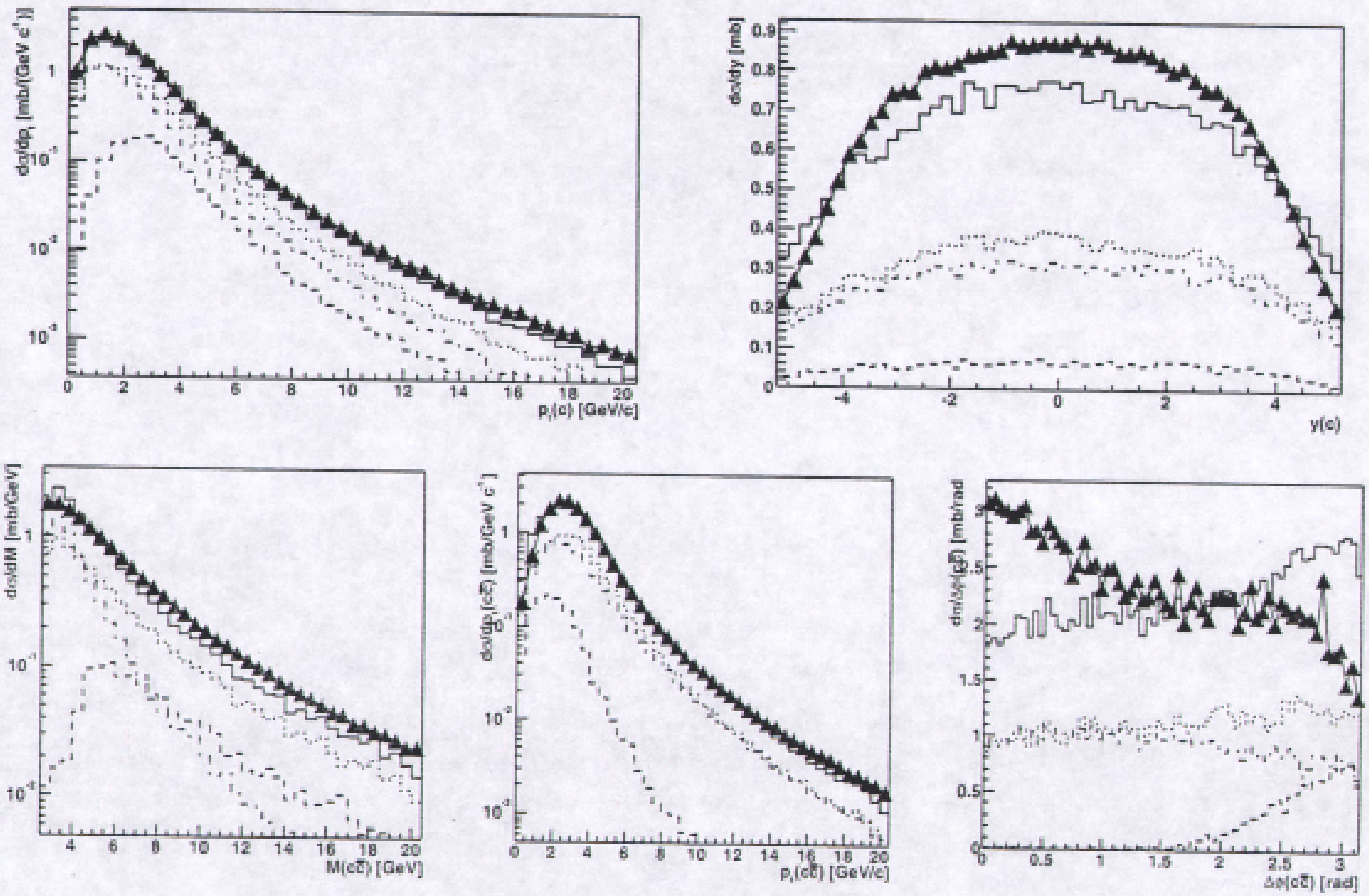
x coverage in charm production





Charm production

NLO vs. Pythia (tuned)



Bottom total rates *in p-p*

$$(I) \;:\; m_b = 4.75 \text{ GeV}, \quad \mu_R = m_b, \quad \mu_F = m_b$$
$$(II) \;:\; m_b = 4.5 \text{ GeV}, \quad \mu_R = m_b, \quad \mu_F = m_b$$
$$(III) \;:\; m_b = 5 \text{ GeV}, \quad \mu_R = m_b, \quad \mu_F = m_b$$
$$(IV) \;:\; m_b = 4.75 \text{ GeV}, \quad \mu_R = 0.5\, m_b, \quad \mu_F = 2\, m_b$$
$$(V) \;:\; m_b = 4.75 \text{ GeV}, \quad \mu_R = 2\, m_b, \quad \mu_F = 0.5\, m_b$$

$\sqrt{S} = 14$ TeV:

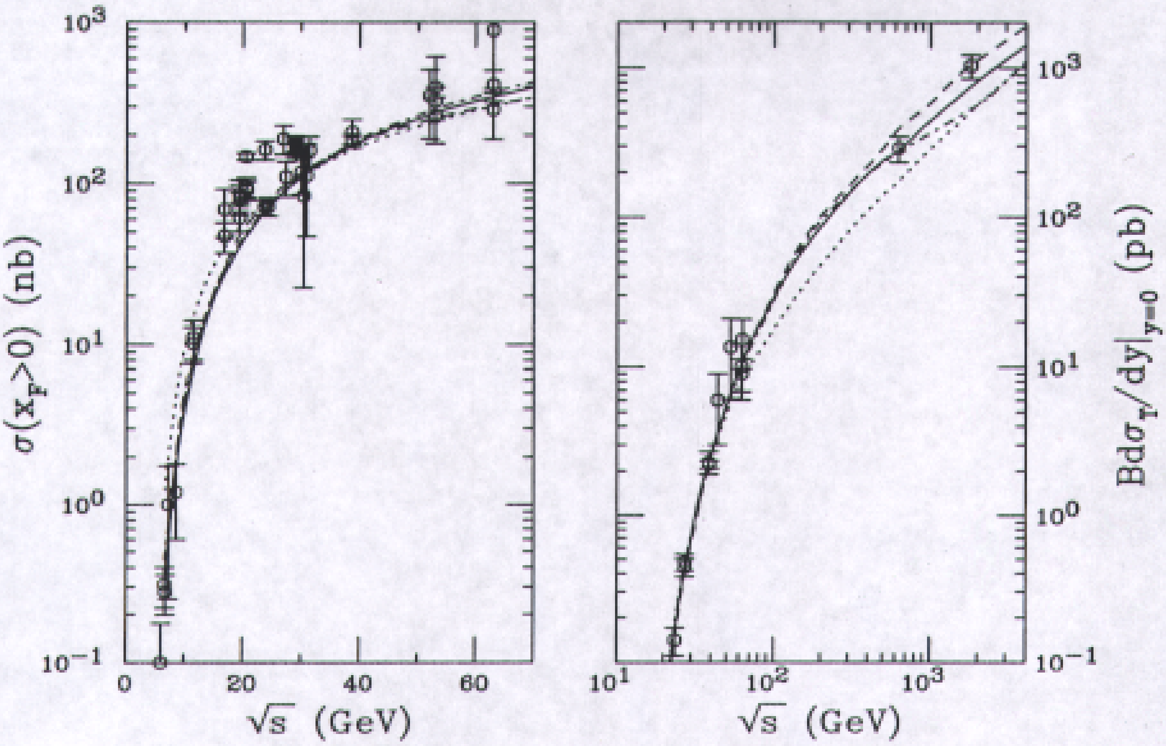
param	σ(mb)	K factor (σ_{NLO}/σ_{LO})
(I)	0.48	2.8
(II)	0.56	2.9
(III)	0.42	2.7
(IV)	0.90	1.8
(V)	0.17	4.1

$\sqrt{S} = 5.5$ TeV:

param (II)	σ(mb)	$R(\Pi) = \sigma_{5.5}/\sigma_{14}$	$R(\Pi)/R(\Pi = \mathrm{I})$
(I)	0.20	0.41	1.
(II)	0.23	0.42	1.01
(III)	0.17	0.40	0.98
(IV)	0.34	0.38	0.94
(V)	0.082	0.47	1.15

PDF dependence $\lesssim 5\%$

Quarkonium production



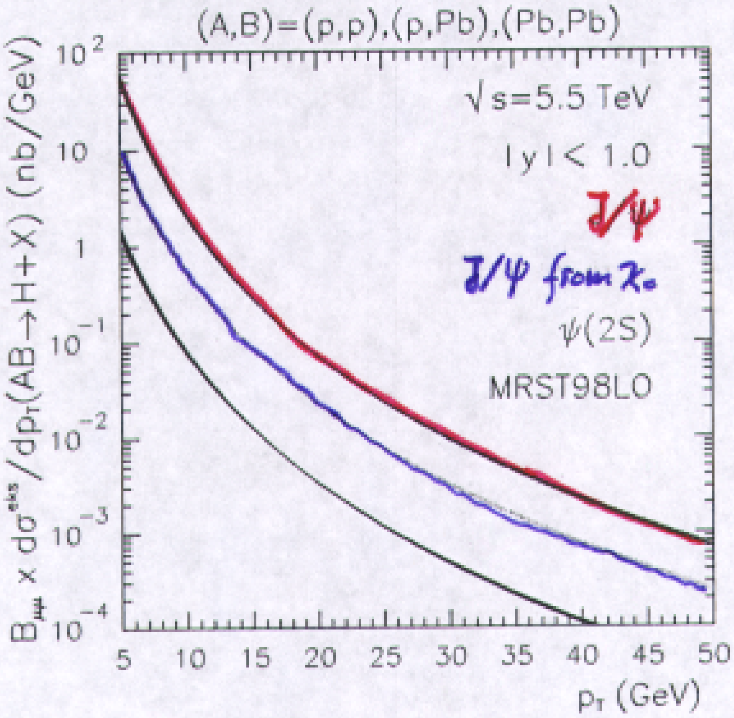
		σ^{dir}/nucleon pair (μb)				$B\sigma^{inc}A^2$ (μb)	
System	$\sqrt{s}$ (TeV)	J/ψ	χ_{c1}	χ_{c2}	ψ'	J/ψ	ψ'
pp	14	32.9	31.8	52.5	7.43	3.18	0.057
pp	8.8	25.0	24.2	39.9	5.65	2.42	0.044
pPb	8.8	19.5	18.9	31.1	4.40	392.3	7.05
pp	7	21.8	21.1	34.9	4.93	2.11	0.038
O+O	7	17.6	17.0	28.1	3.98	436.2	7.84
pp	6.3	20.5	19.9	32.8	4.63	1.99	0.036
Ar+Ar	6.3	15.0	14.5	23.9	3.38	2321	41.7
pp	6.14	20.2	19.6	32.3	4.56	1.96	0.035
Kr+Kr	6.14	13.7	13.2	21.8	3.08	9327	167.6
pp	5.84	19.6	19.0	31.3	4.42	1.90	0.034
Sn+Sn	5.84	12.8	12.4	20.4	2.89	17545	315.2
pp	5.5	18.9	18.3	30.2	4.26	1.83	0.033
Pb+Pb	5.5	11.7	11.3	18.7	2.64	48930	879

$\Upsilon, \Upsilon', \Upsilon''$ cross sections

Table 6: The direct cross section per nucleon pair and the dilepton cross section per nucleon multiplied by A^2 for the minimum bias lepton pair cross section. The results are given for $\Upsilon 1$. We compare pp to pA and AA interactions.

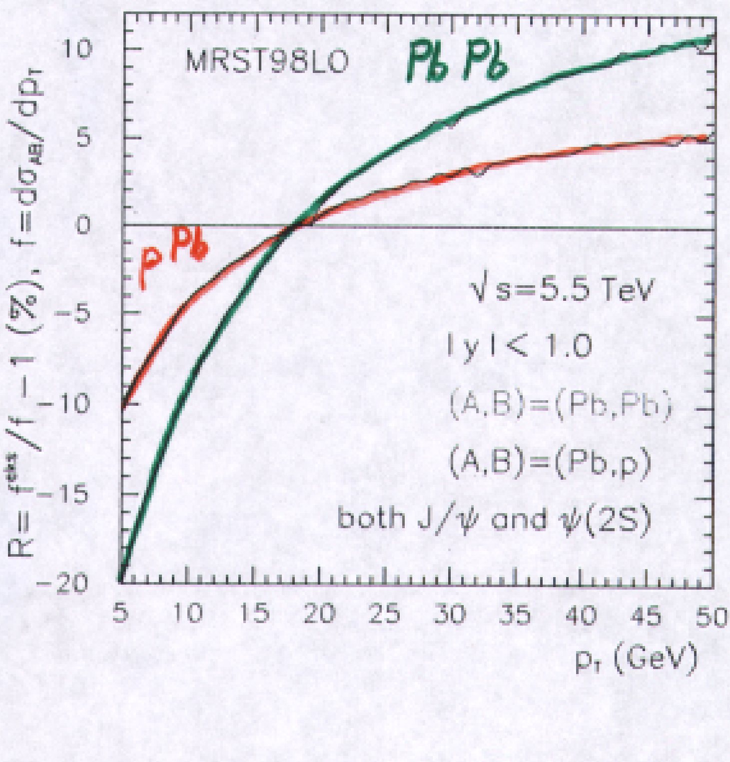
		$\sigma^{\rm dir}$/nucleon pair (μb)					$B\sigma^{\rm inc} A^2$ (μb)		
System	$\sqrt{s}$ (TeV)	Υ	Υ'	Υ''	$\chi_b(1P)$	$\chi_b(2P)$	Υ	Υ'	Υ''
pp	14	0.43	0.27	0.16	0.89	0.69	0.020	0.0050	0.0030
pp	8.8	0.29	0.18	0.11	0.60	0.47	0.014	0.0040	0.0020
pPb	8.8	0.25	0.16	0.097	0.52	0.41	2.51	0.65	0.37
pp	7	0.23	0.15	0.090	0.48	0.38	0.011	0.0029	0.0016
O+O	7	0.21	0.13	0.081	0.44	0.34	2.57	0.66	0.38
pp	6.3	0.21	0.14	0.082	0.44	0.34	0.010	0.0026	0.0015
Ar+Ar	6.3	0.18	0.12	0.070	0.38	0.29	13.8	3.59	2.02
pp	6.14	0.21	0.13	0.080	0.43	0.33	0.0099	0.0026	0.0014
Kr+Kr	6.14	0.17	0.11	0.066	0.35	0.28	57.4	14.8	8.38
pp	5.84	0.20	0.12	0.076	0.41	0.32	0.0094	0.0024	0.0014
Sn+Sn	5.84	0.16	0.10	0.062	0.33	0.26	108.1	28.0	15.8
pp	5.5	0.19	0.12	0.070	0.39	0.30	0.0090	0.0020	0.0013
Pb+Pb	5.5	0.15	0.094	0.057	0.31	0.24	304	78.8	44.4

$p_\perp$ - spectrum of J/ψ



$p_\perp$ - spectrum sensitive to nPDF

$$\frac{d\sigma^{AB}/dp_t - d\sigma^{pp}/dp_t}{d\sigma^{pp}/dp_t}$$

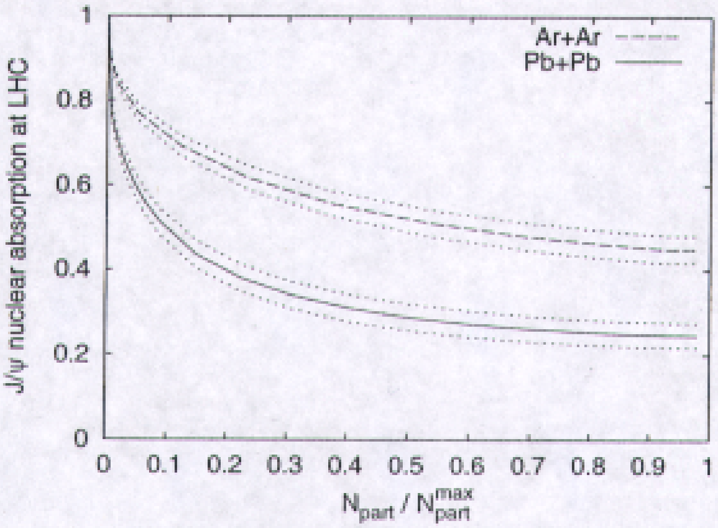


in σ_{abs}.

b (fm)	$S_{J/\psi}$ SPS	RHIC	LHC
$\langle b \rangle$	0.52 ± 0.03	0.42 ± 0.03	0.29 ± 0.03
0	0.47 ± 0.03	0.37 ± 0.04	0.25 ± 0.03
1	0.47 ± 0.03	0.37 ± 0.04	0.25 ± 0.03
2	0.47 ± 0.03	0.37 ± 0.04	0.25 ± 0.03
3	0.48 ± 0.03	0.38 ± 0.04	0.25 ± 0.03
4	0.48 ± 0.03	0.38 ± 0.04	0.25 ± 0.03
5	0.49 ± 0.03	0.39 ± 0.04	0.26 ± 0.03
6	0.50 ± 0.03	0.40 ± 0.04	0.27 ± 0.03
7	0.52 ± 0.03	0.42 ± 0.04	0.29 ± 0.03
8	0.54 ± 0.03	0.44 ± 0.03	0.31 ± 0.03
9	0.57 ± 0.03	0.47 ± 0.03	0.34 ± 0.03
10	0.60 ± 0.03	0.51 ± 0.03	0.38 ± 0.03
11	0.65 ± 0.03	0.57 ± 0.03	0.44 ± 0.03
12	0.71 ± 0.02	0.63 ± 0.03	0.51 ± 0.03

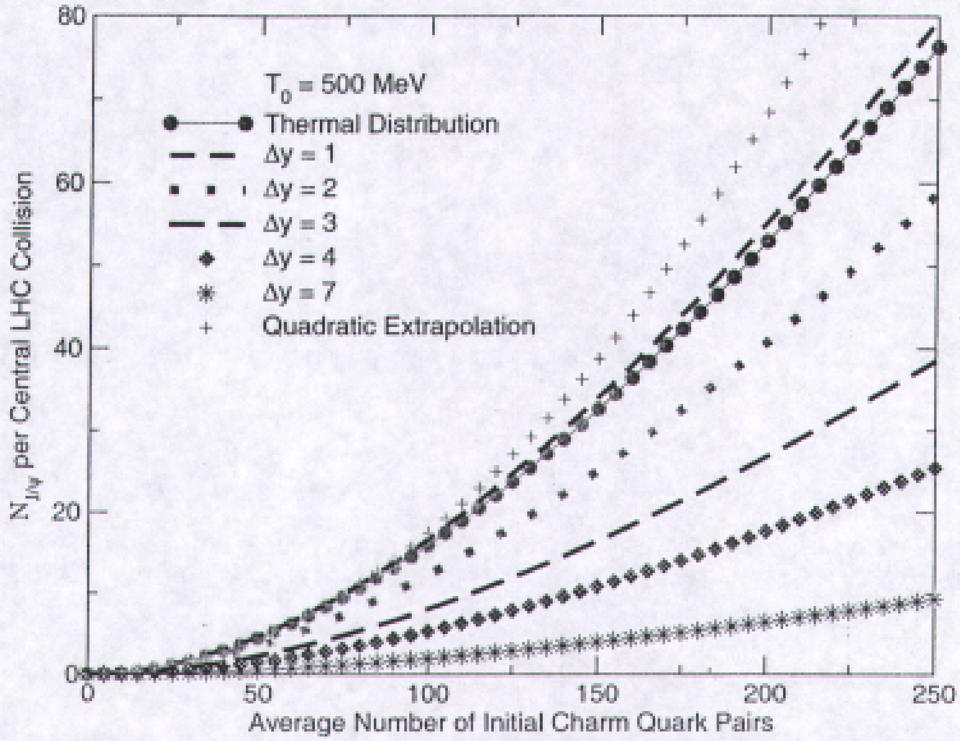
Base line: J/Ψ suppression   input $\sigma_{abs}(\sqrt{s})$

Survival probability



"Kinetic model" : $\frac{dN_{J/\psi}}{d\tau} = \lambda_F \frac{N_c N_{\bar{c}}}{V(\tau)} - \lambda_D N_{J/\psi} \rho_g$

predicts J/Ψ enhancement

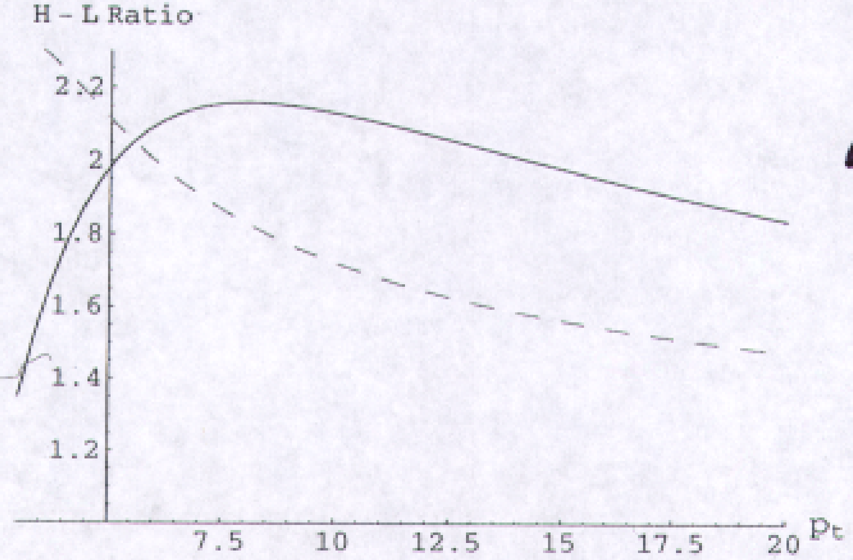


(right-hand side) models.

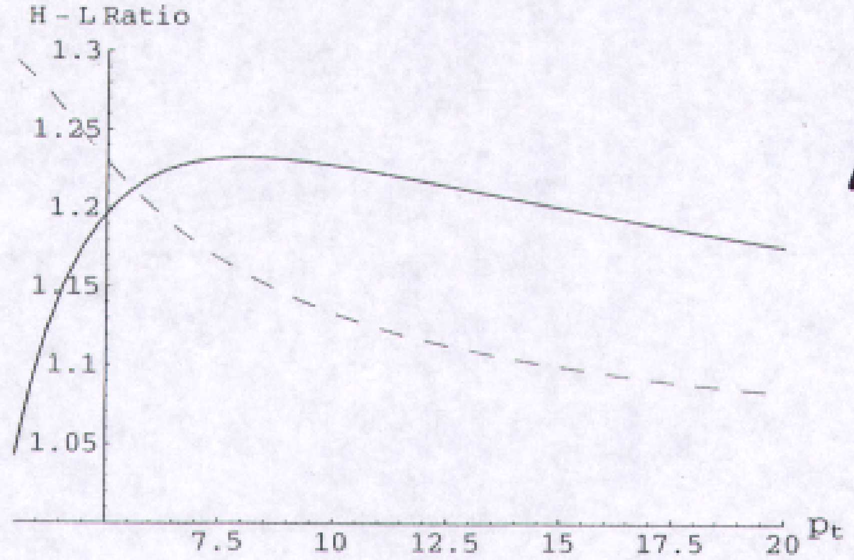
	$\frac{dN_{J/\psi}/dy}{dN_{c\bar{c}}(0)/dy}$ (Statistical)			$\frac{N_{J/\psi}}{N_{c\bar{c}}(0)}$ (Kinetic, LO Charm)		
b (fm)	25	18.75	12.5	200	150	100
0	0.656	0.370	0.165	4.0	2.26	1.03
1	0.637	0.359	0.160	3.85	2.19	1.00
2	0.586	0.330	0.147	3.51	2.00	0.91
3	0.515	0.290	0.130	3.04	1.73	0.79
4	0.434	0.245	0.109	2.50	1.43	0.65
5	0.351	0.198	0.088	1.97	1.12	0.51
6	0.270	0.152	0.068	1.46	0.84	0.38
7	0.196	0.110	0.050	1.01	0.58	0.27
8	0.132	0.075	0.034	0.65	0.38	0.18
9	0.082	0.046	0.021	0.38	0.22	0.10
10	0.045	0.026	0.012	0.20	0.12	0.057
11	0.022	0.013	0.0061	0.087	0.054	0.028
12	0.0097	0.0058	0.0029	0.034	0.022	0.012
13	0.0045	0.0029	0.0016	0.011	0.0075	0.0041
14	0.0028	0.0019	0.0012	0.0021	0.0013	6.8×10^{-4}
15	0.0025	0.0018	0.0012	1.8×10^{-4}	1.0×10^{-4}	5.1×10^{-5}

Dead cone effect

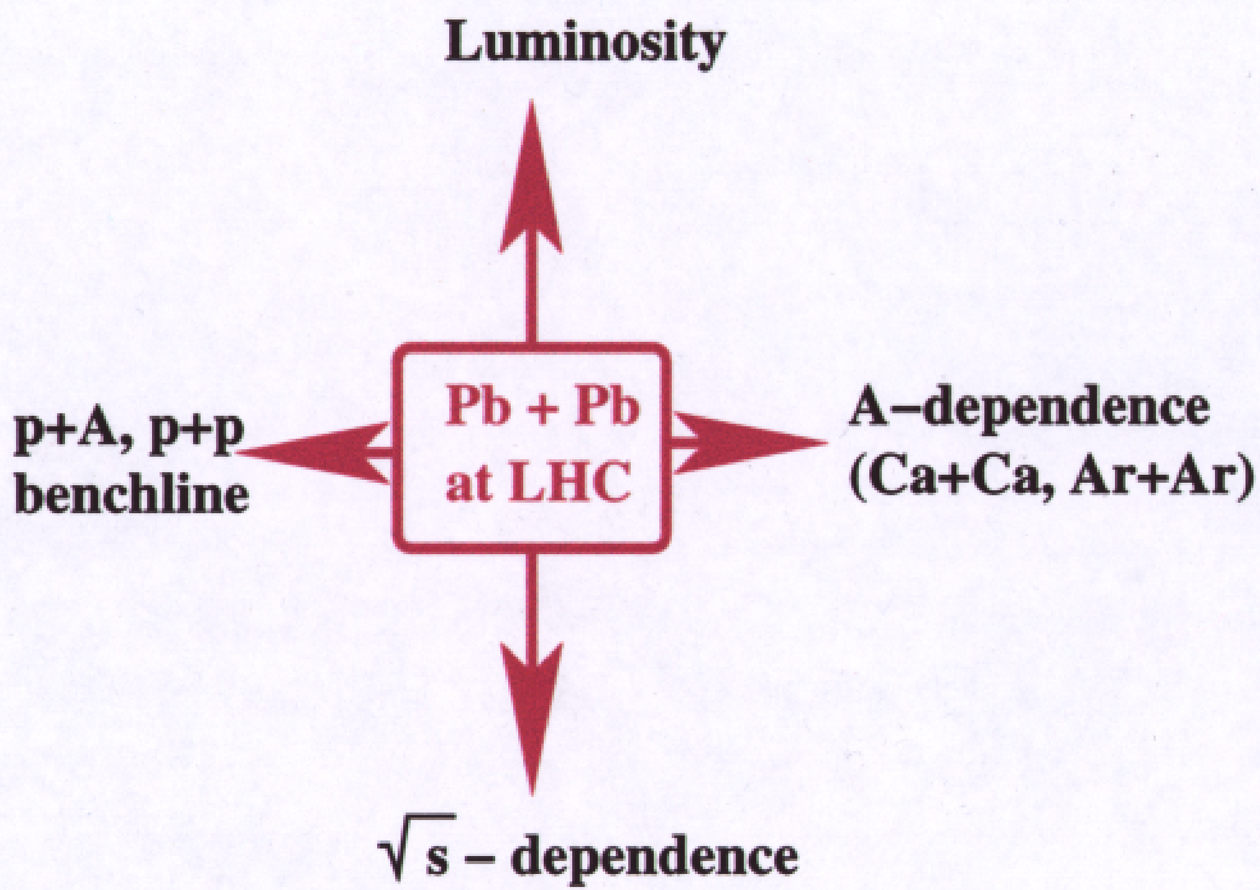
charm quark looses a fraction Q less energy than light quark



L = 5 fm



L = 2 fm


Luminosity
p+A, p+p
benchline
Pb + Pb
at LHC
A−dependence
(Ca+Ca, Ar+Ar)
$\sqrt{s}$ – dependence

Priorities ?

Priorities (current view)

1. Pb+Pb: accumulate $\sim O(1)$ nb^{-1} integrated luminosity
(1 months at design luminosity)

2. p+A: establish benchmark
(2-4 weeks at design luminosity)

3. Pb+Pb: increase statistics

4. A-dependence: e.g. Ca+Ca and Sn+Sn

5. $\sqrt{s}$-dependence

Final Remarks

- ▲ TH readiness for LHC
  - ● YR → documents state of the art in 2002
    → assesses what remains to be done
  - ● developments till 2007
    → experience gained at RHIC
    → physics performance studies at LHC Exp.
  - ⇒ assess need for follow-up

- ▲ other HIC - observables
  - ● soft probes
  - ● fluctuations and correlations

- ▲ YR is also LHC outreach
  document a dedicated long-term HI programme
  to solicit a dedicated large-scale TH support