QCD: Experiment

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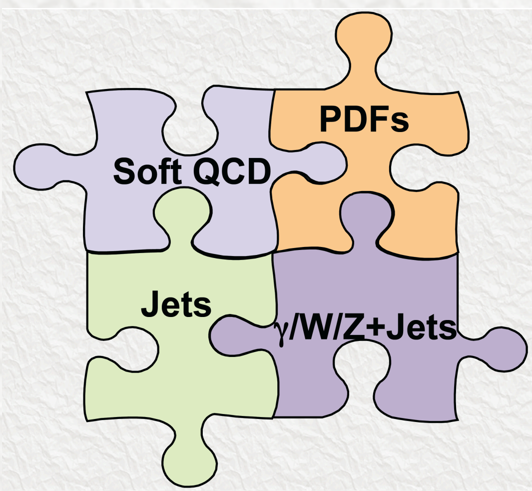
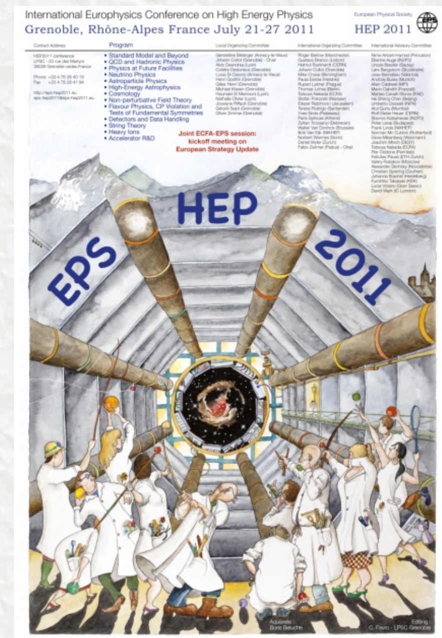


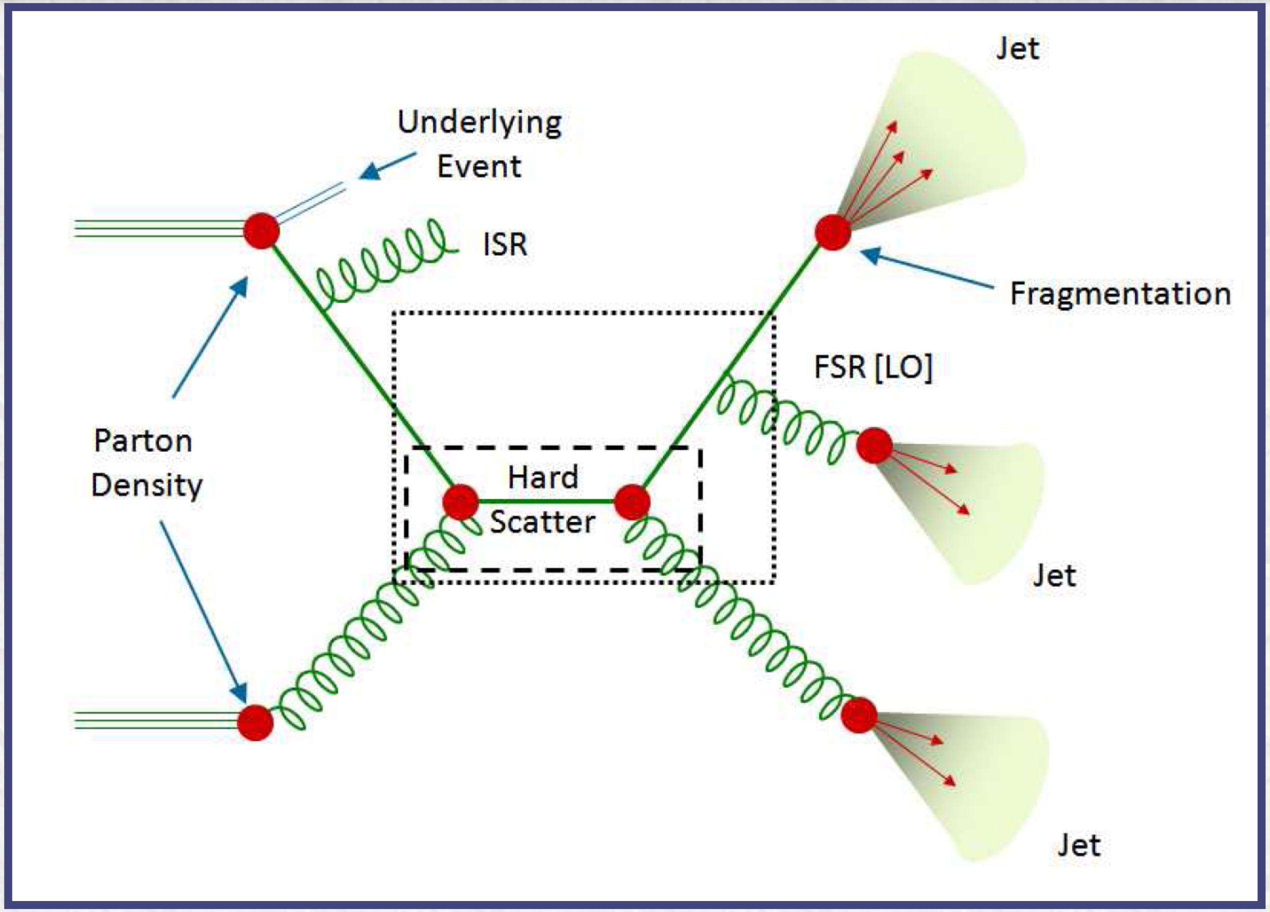
HEP2011
Grenoble
July 21-27, 2011



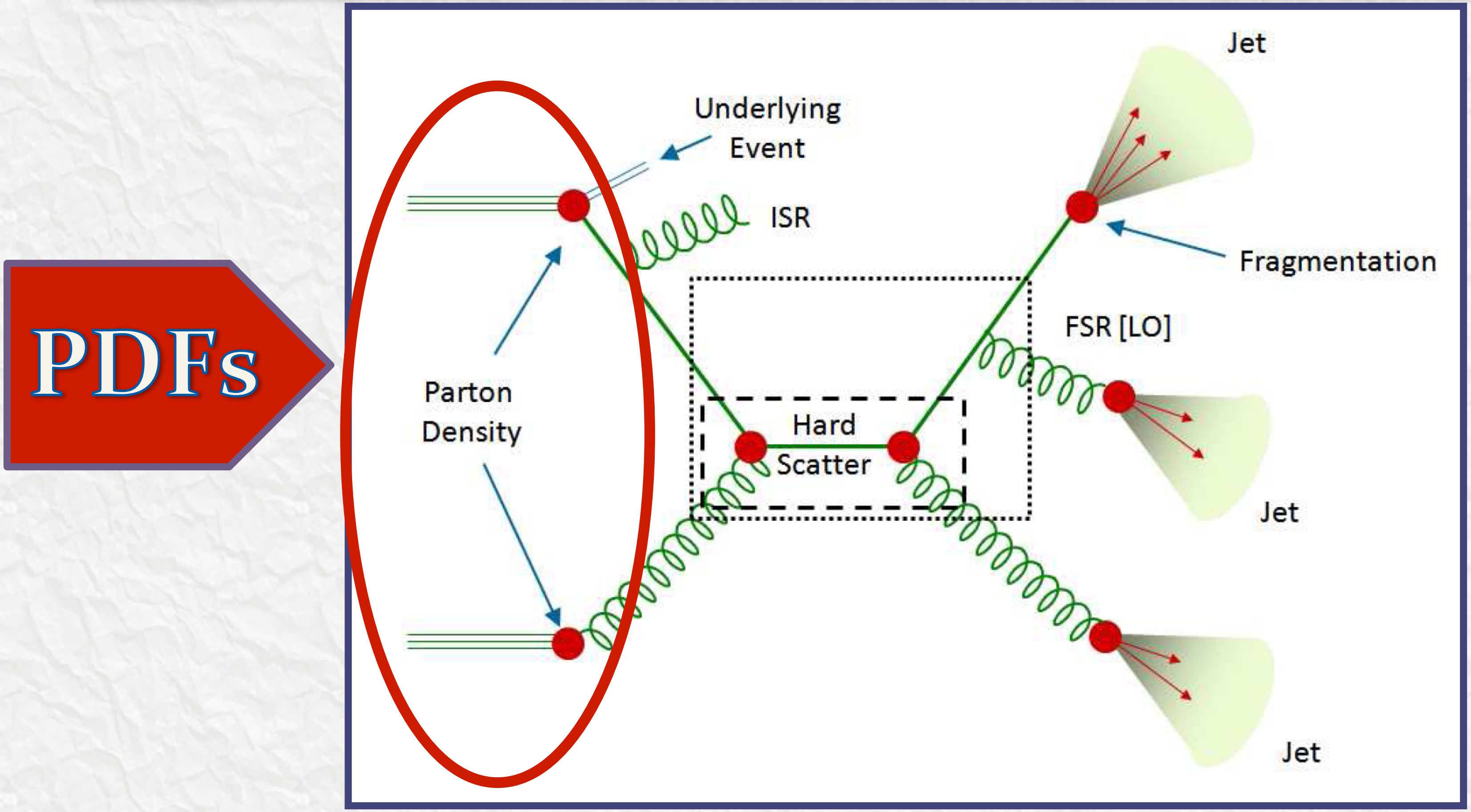
The QCD Parallel Program

- 68 presentations just in the QCD parallel program
  - + many posters
- It is impossible to cover all QCD results presented in this conference in a 25-minute talk
  - Apologies for the ones left out
  - Thanks to all speakers for the excellent presentations and the fruitful discussions!
  - References (arXiv/pubs or physics analysis reports) for the results presented in this talk are provided so you can get more details
- QCD results are also included in other plenary talks
  - W and Z Physics – Juan Alcaraz
    - Covered W/Z+HF, EWK measurements related to PDF tuning
  - Standard Model Theory for Collider Physics – Giulia Zanderighi
    - Status of strong coupling constant…
  - Flavor Physics at the LHC – Guy Wilkinson
  - Flavor Physics at the Tevatron – Diego Tonelli

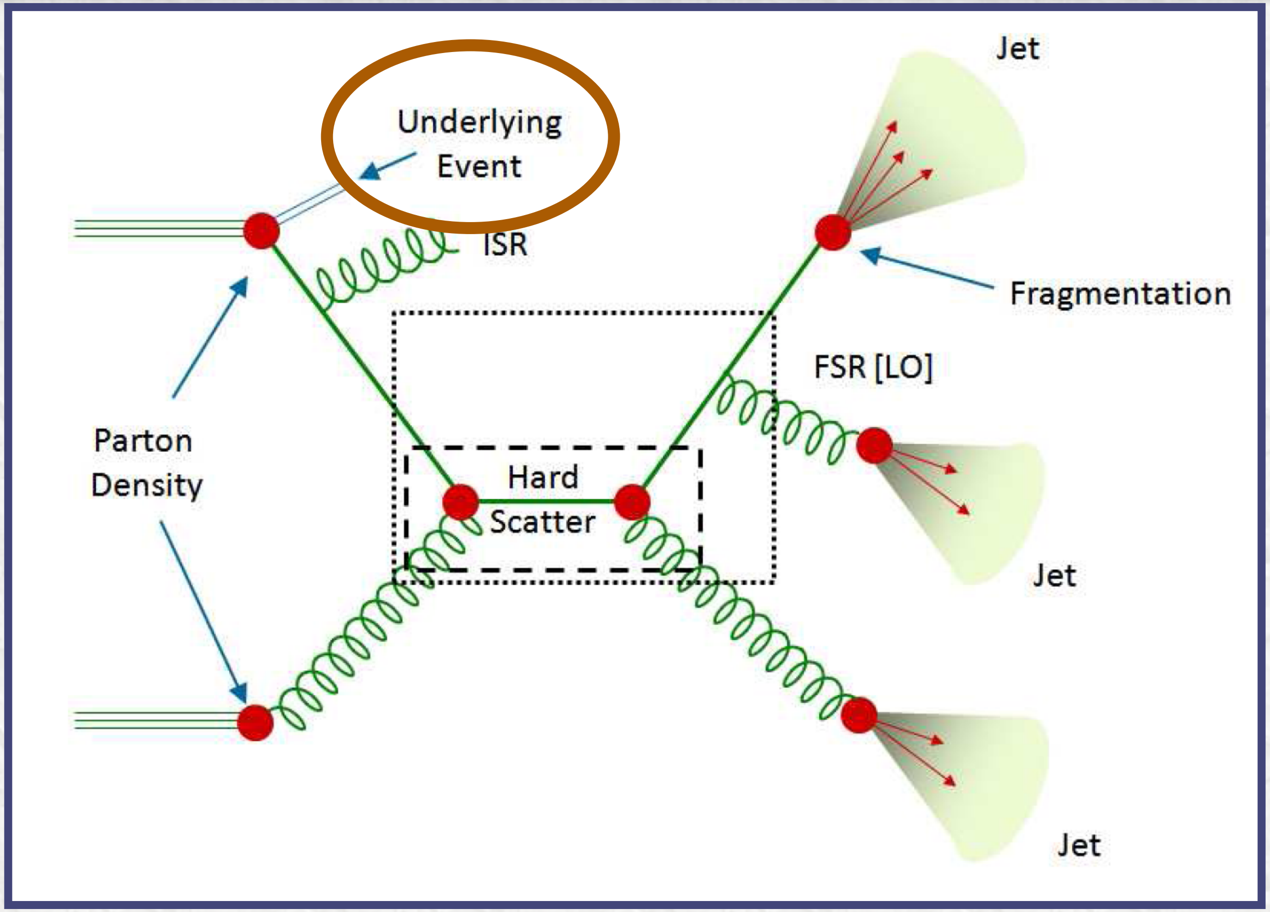
QCD at Hadron Colliders



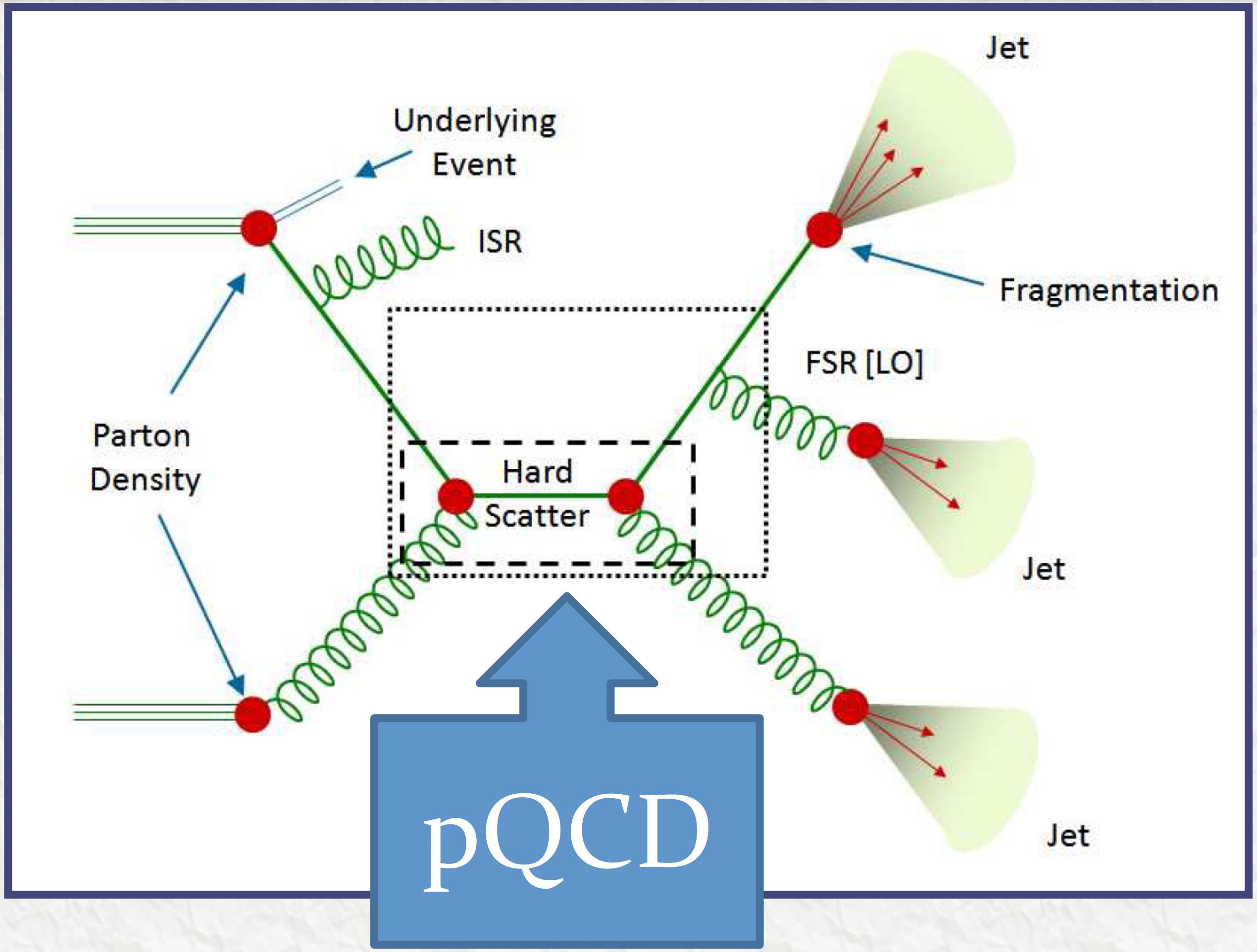
QCD at Hadron Colliders



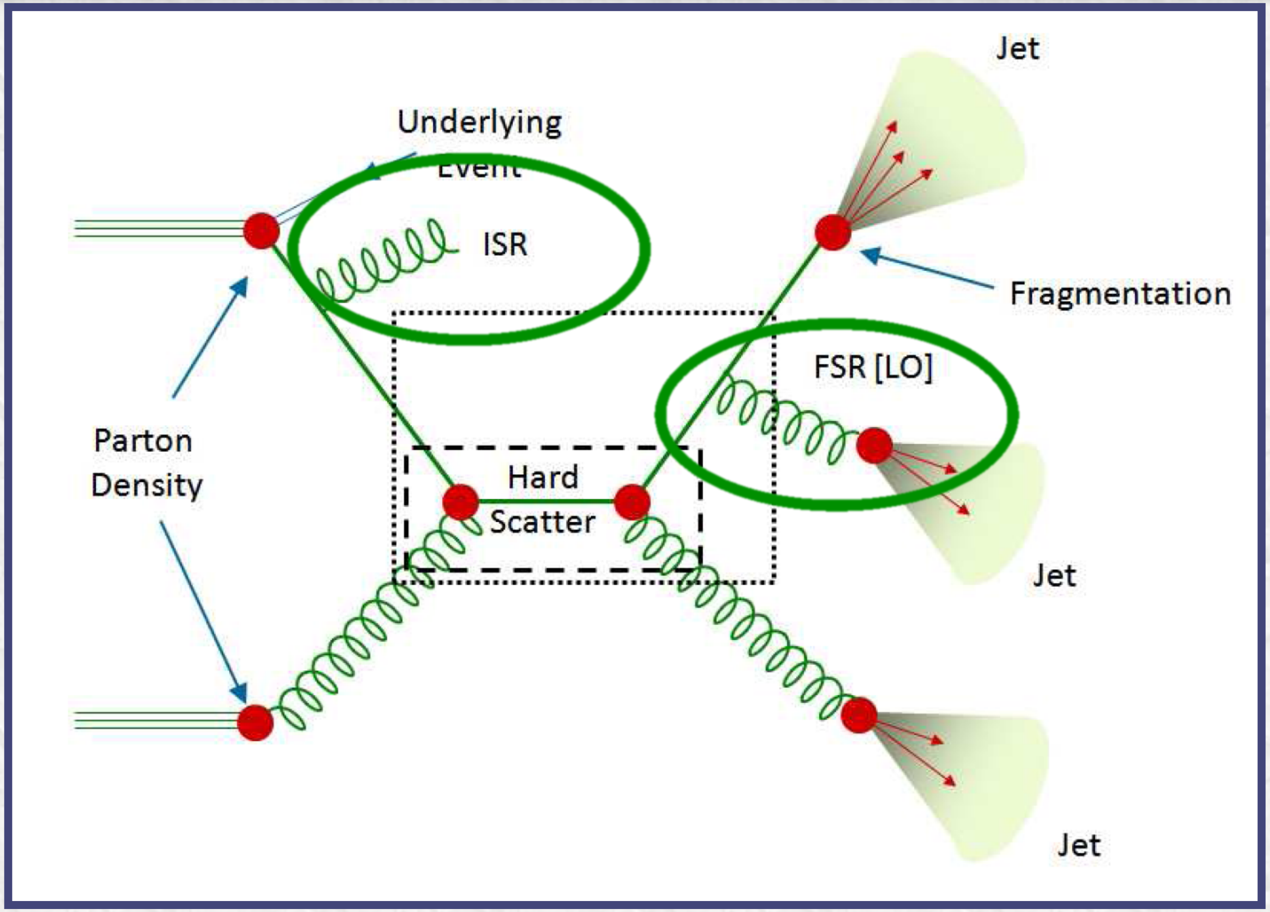
QCD at Hadron Colliders



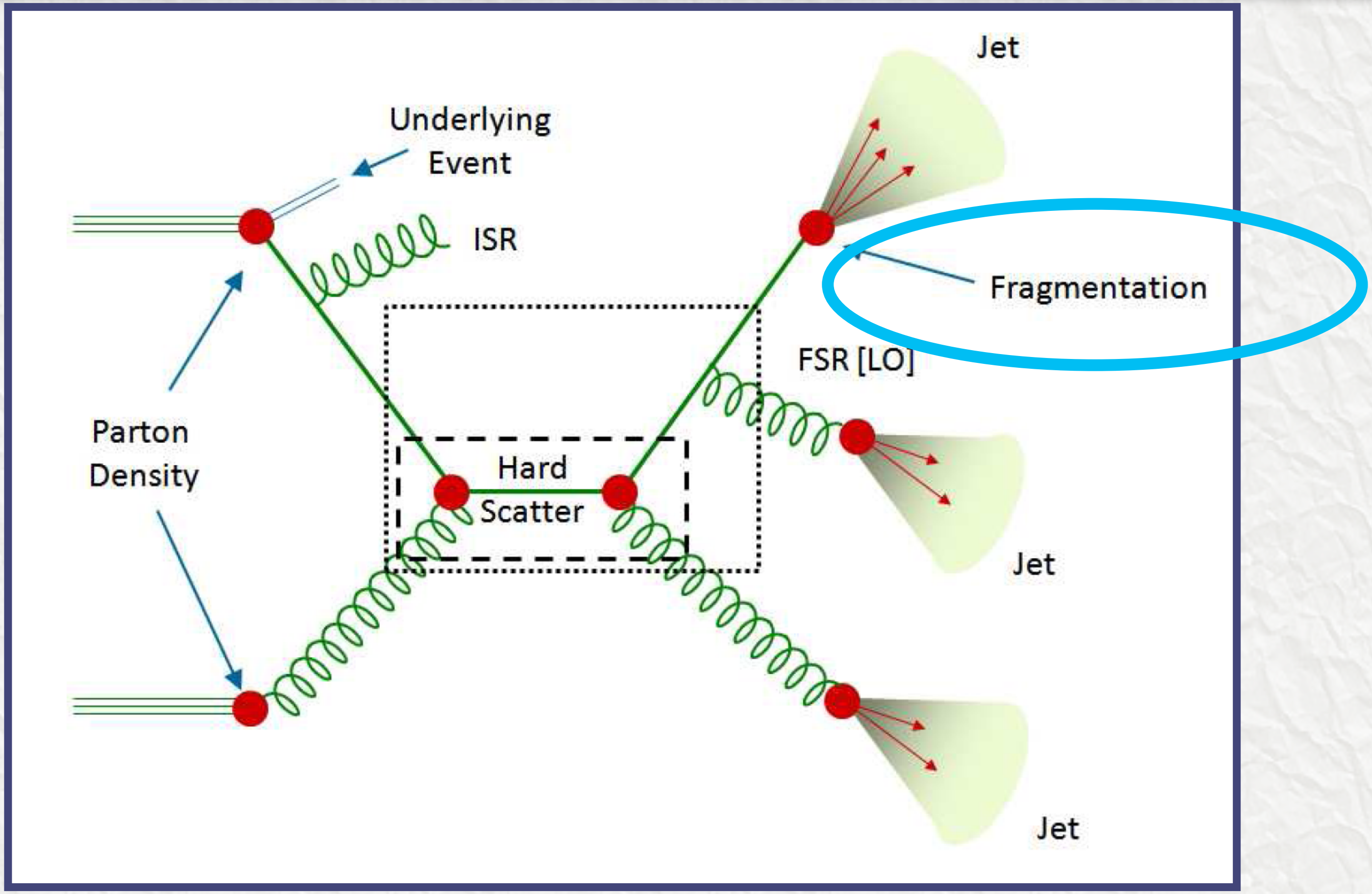
QCD at Hadron Colliders



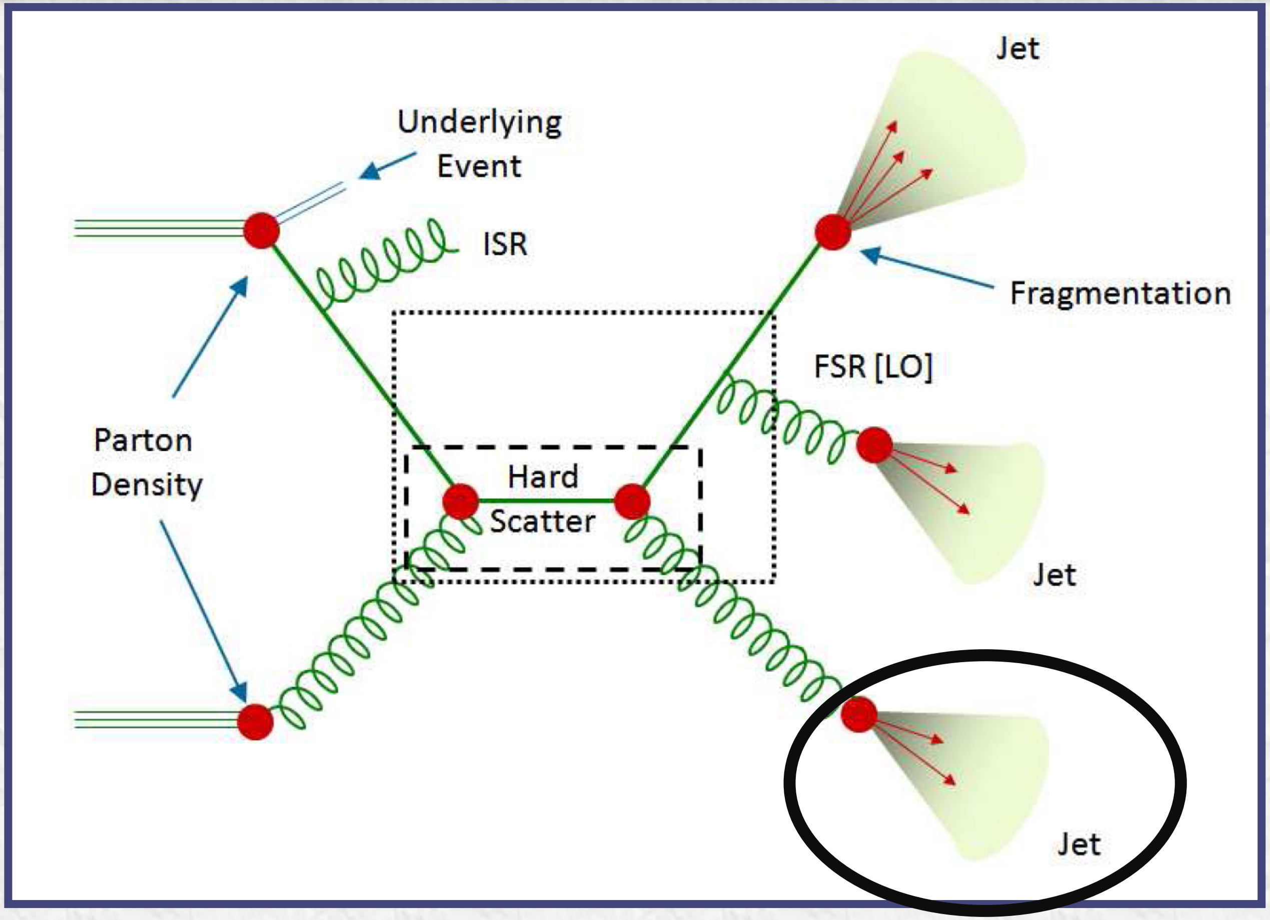
QCD at Hadron Colliders



QCD at Hadron Colliders

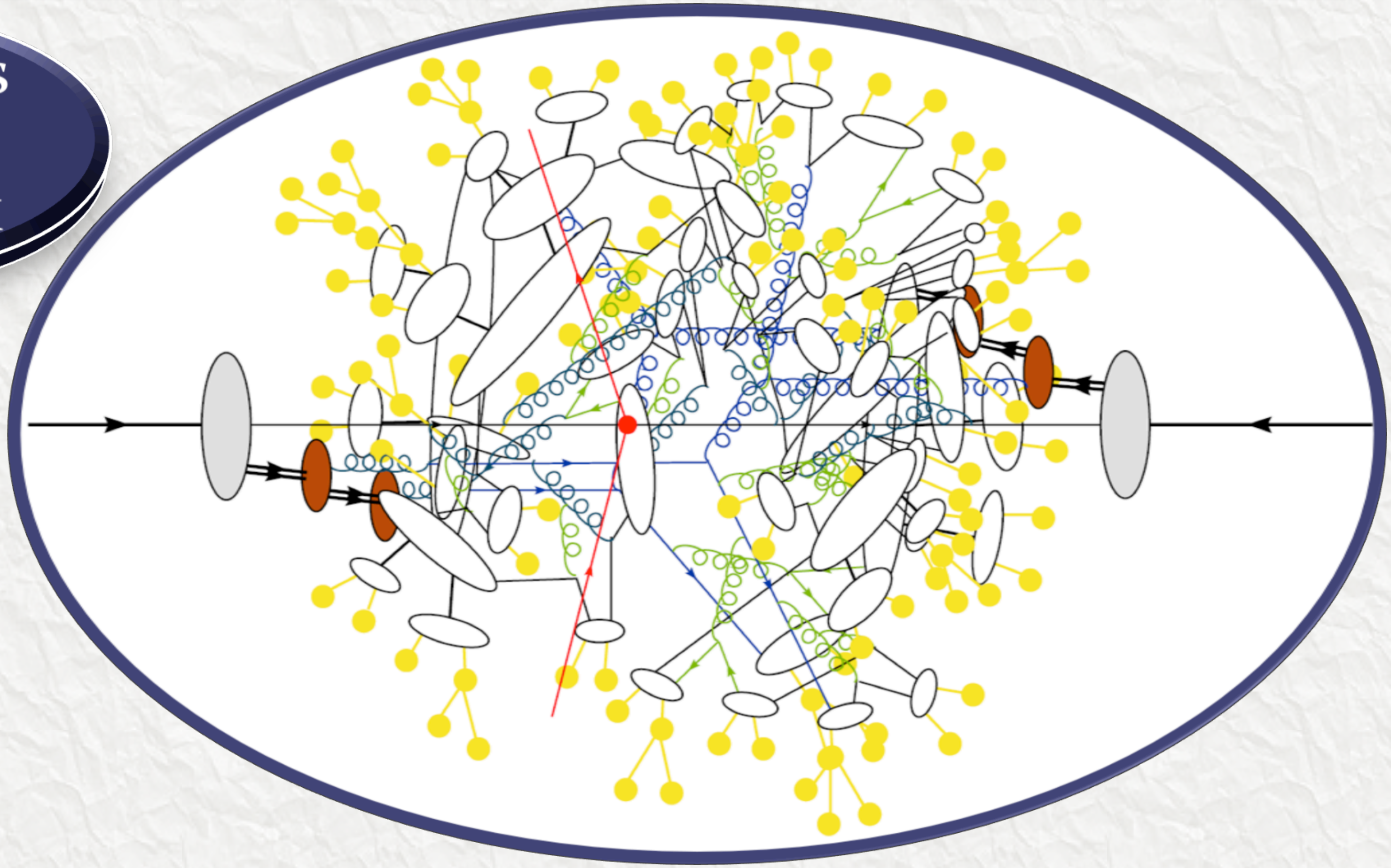


QCD at Hadron Colliders



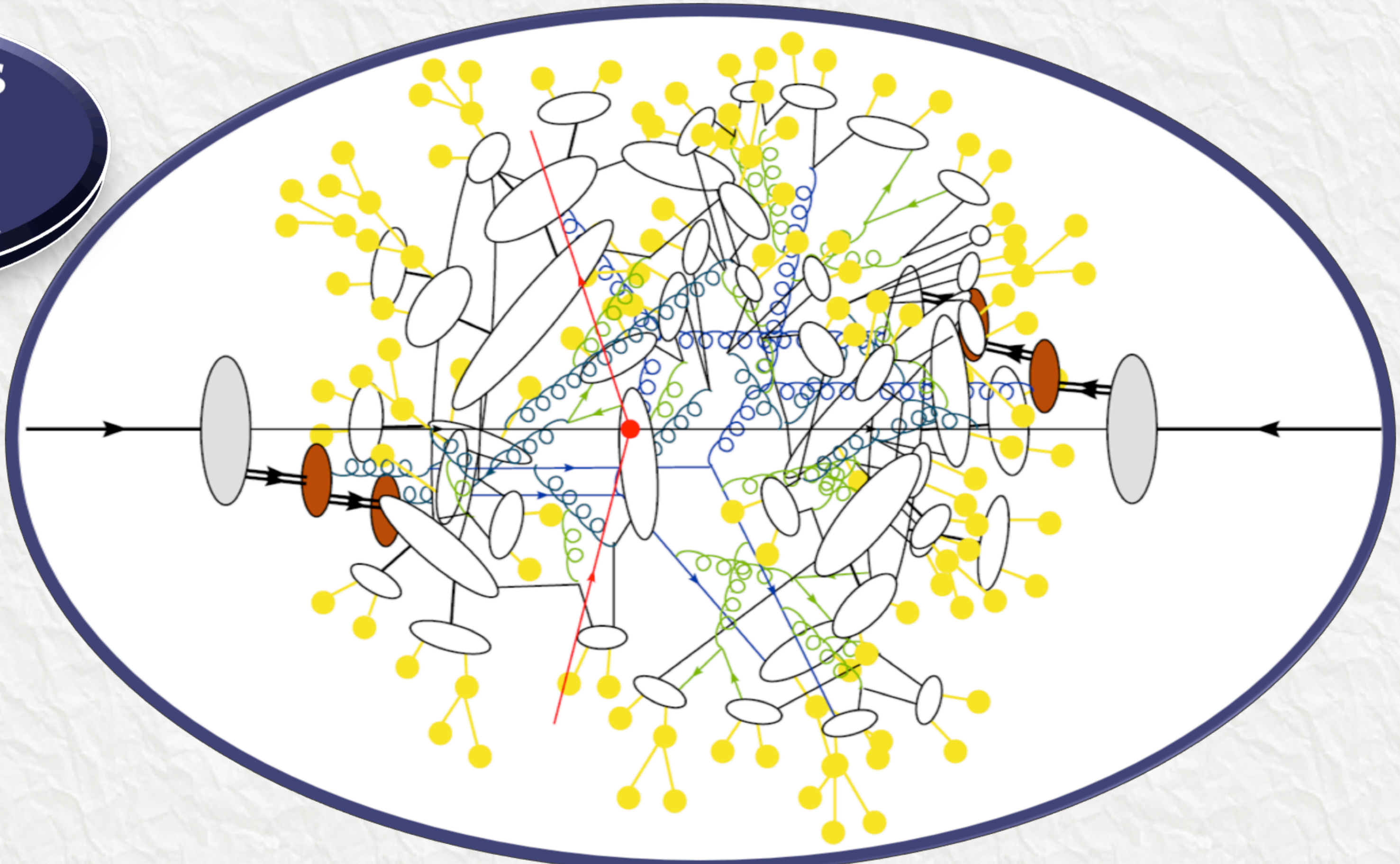
QCD at Hadron Colliders

Reality is more complex



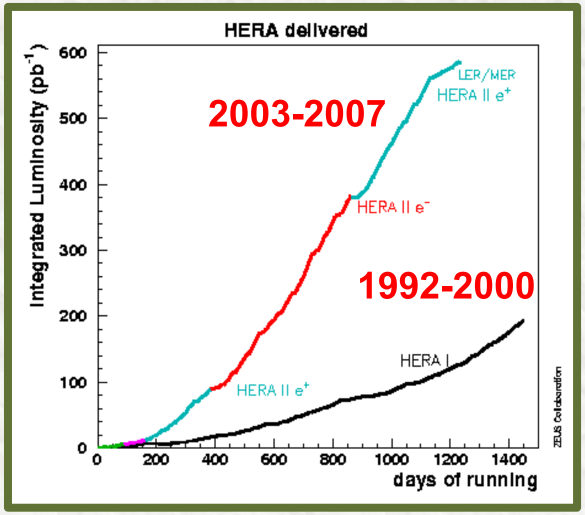
QCD at Hadron Colliders

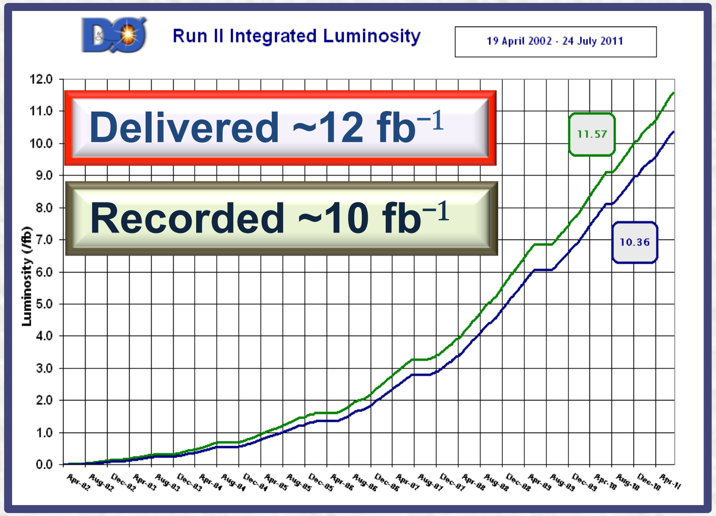
Reality is more complex

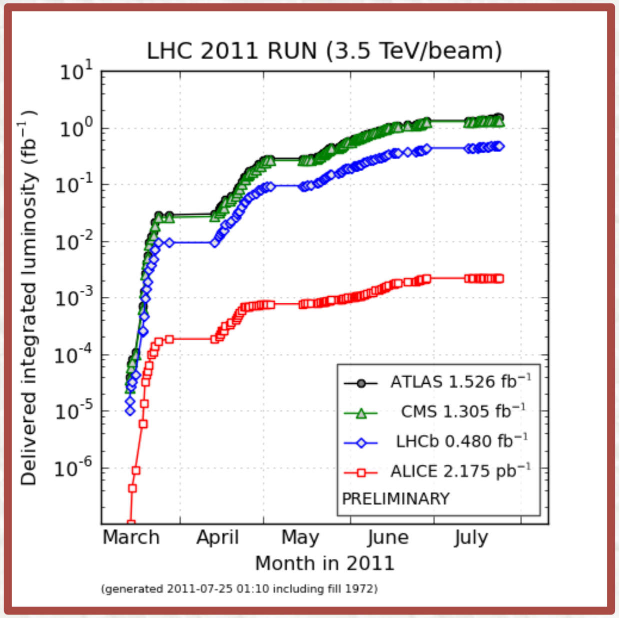


- Understanding of QCD is important for
  - Interpretation of data
  - Precision studies
  - Searches for New Physics

HERA – Tevatron – LHC







Running Period: 1992 – 2007

p 920(820) GeV

(Low Energy Runs: 575, 460 GeV)

e^+/e^- 27.5 GeV

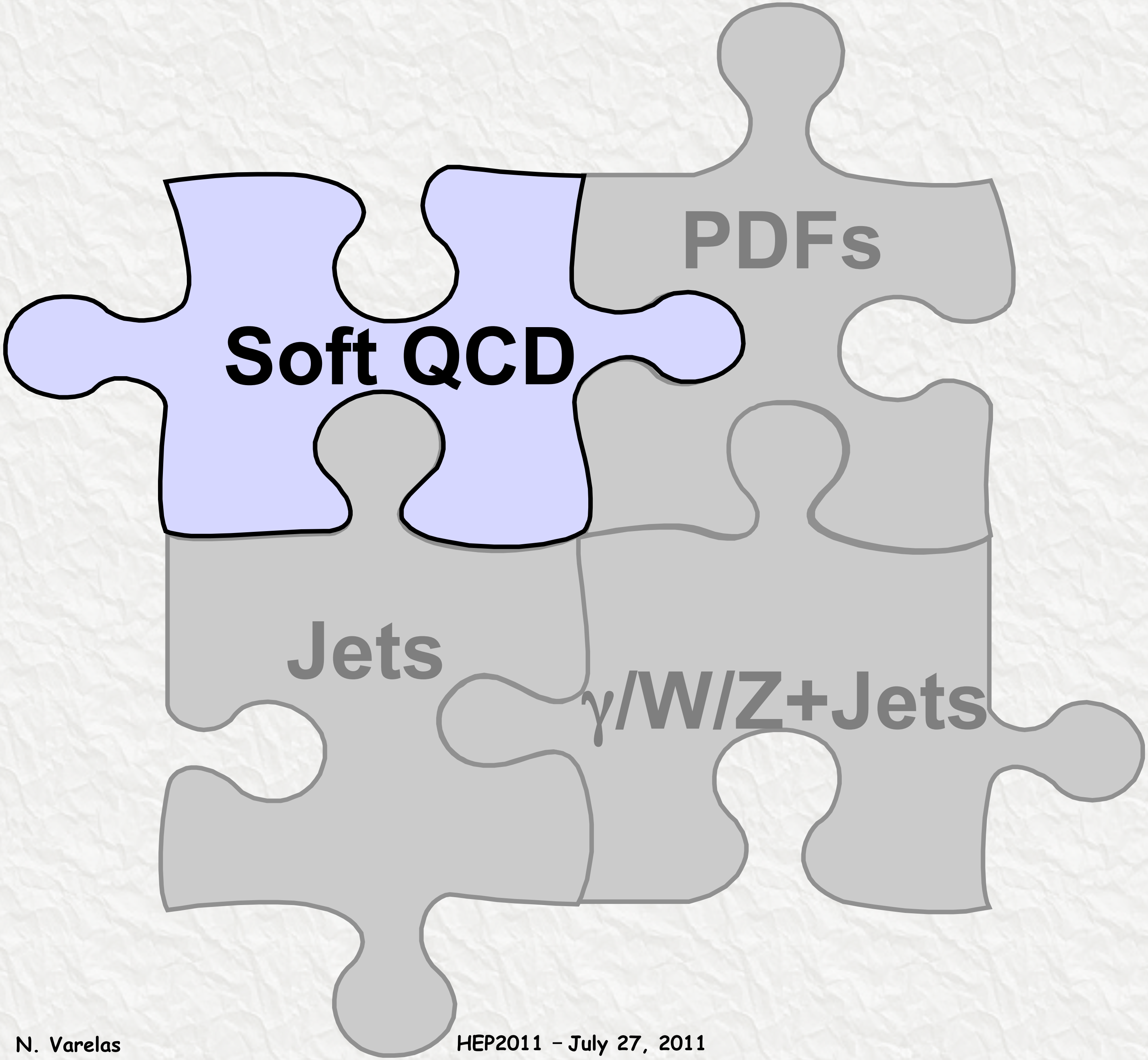
→ $\sqrt{s}$ = 318 GeV

$$\sqrt{s} = 0.9 \text{ TeV} \Rightarrow \text{ Luminosity} \sim 10\ \mu b^{-1}$$

$$\sqrt{s} = 2.36 \text{ TeV} \Rightarrow \text{ Luminosity} < 1\ \mu b^{-1}$$

$$\sqrt{s} = 7 \text{ TeV (2010)} \Rightarrow \text{ Luminosity} \sim 46\ pb^{-1}$$

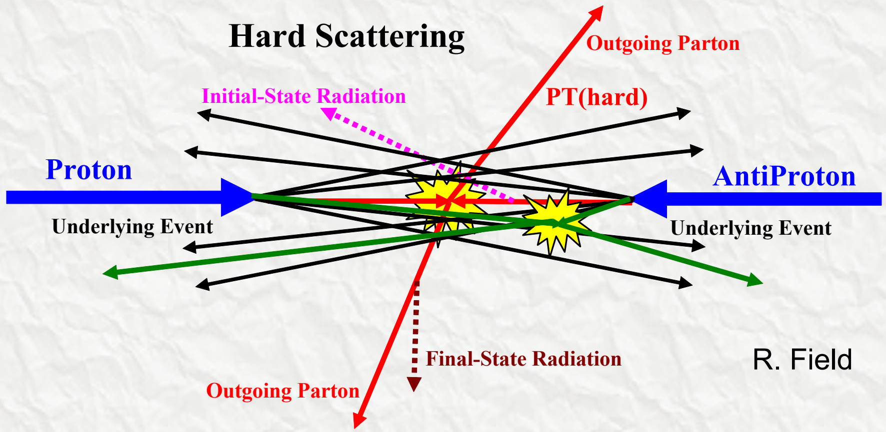
$$\sqrt{s} = 7 \text{ TeV (2011)} \Rightarrow \text{ Luminosity} > 1.5\ fb^{-1}$$


PDFs
Soft QCD
Jets
γ/W/Z+Jets

The Underlying Event

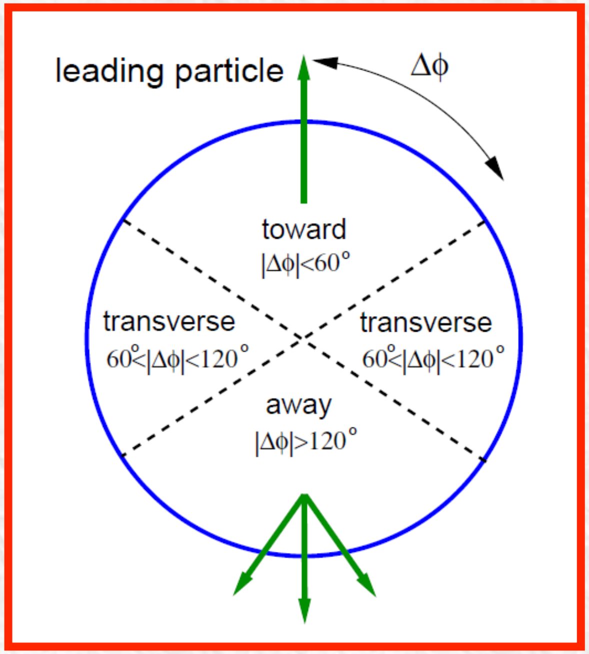
The "underlying event" consists of everything else but the hard interaction

- the "beam-beam remnants"
- particles arising multiple parton interactions (MPI)



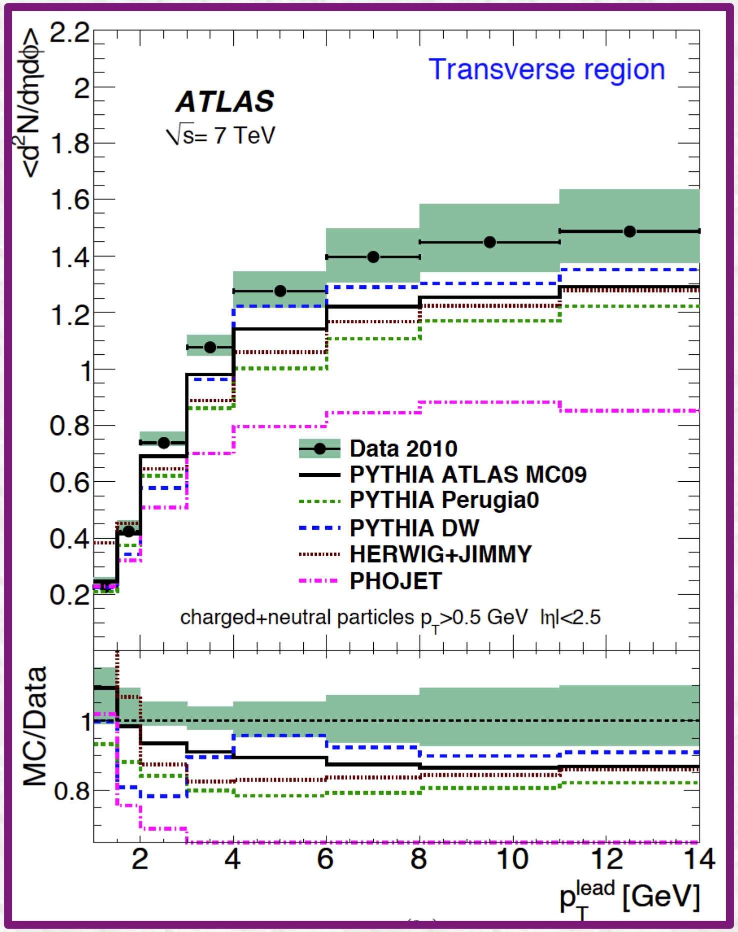
R. Field

- **Define three regions:**
  - "toward"
  - "away"
  - "transverse"
    - Sensitive to UE



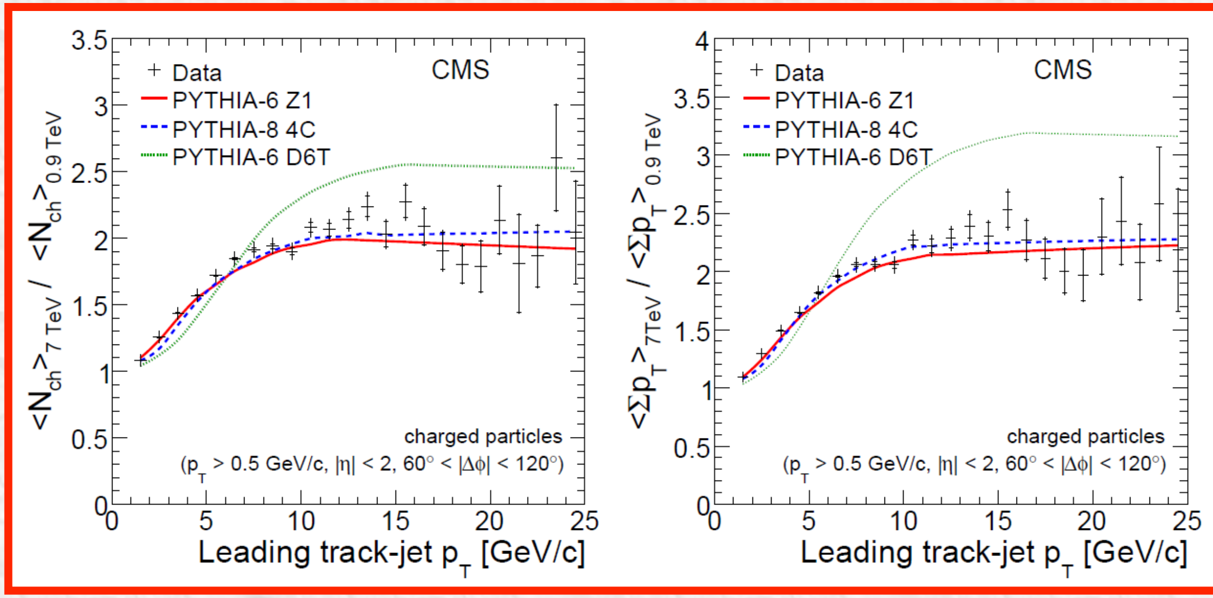
Underlying Event at LHC (0.9-7 TeV)

ATLAS: arXiv: 1103.1816



$d^2N_{ch}/d\eta d\phi$ vs p_T (7 TeV)
$d^2N_{ch}/d\eta d\phi$ vs p_T (900 GeV)

$d^2\Sigma p_T/d\eta d\phi$ vs p_T (7 TeV)
$d^2\Sigma p_T/d\eta d\phi$ vs p_T (900 GeV)



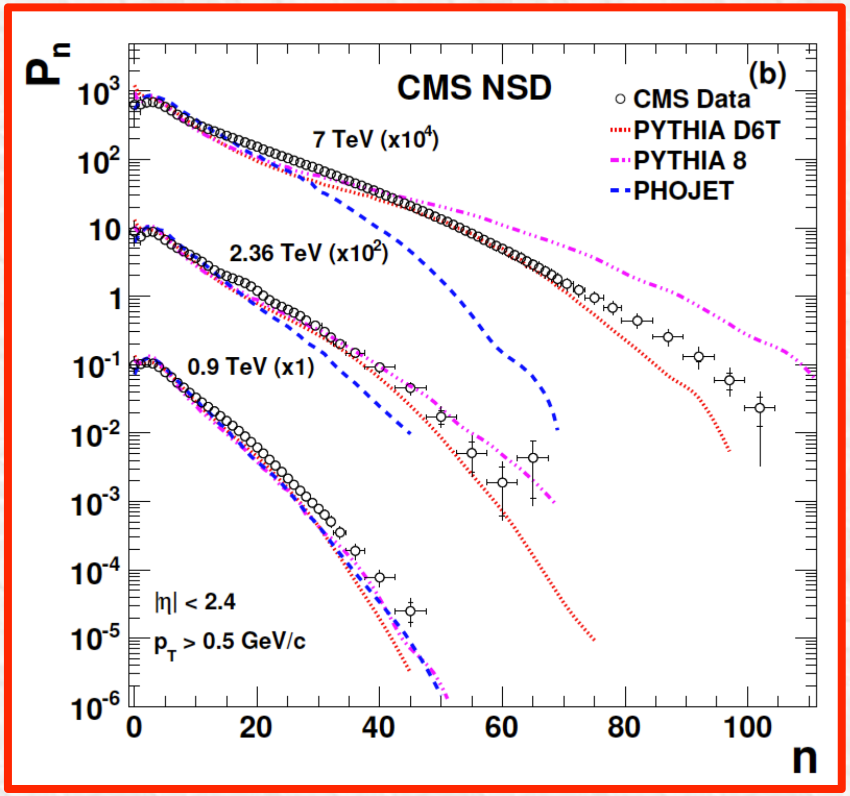
CMS: arXiv: 1107.0330

- **A factor of ~2 increase in activity from 0.9 to 7 TeV**
- **Shape predicted well from tunes 4C and Z1 (but not from the older D6T)**

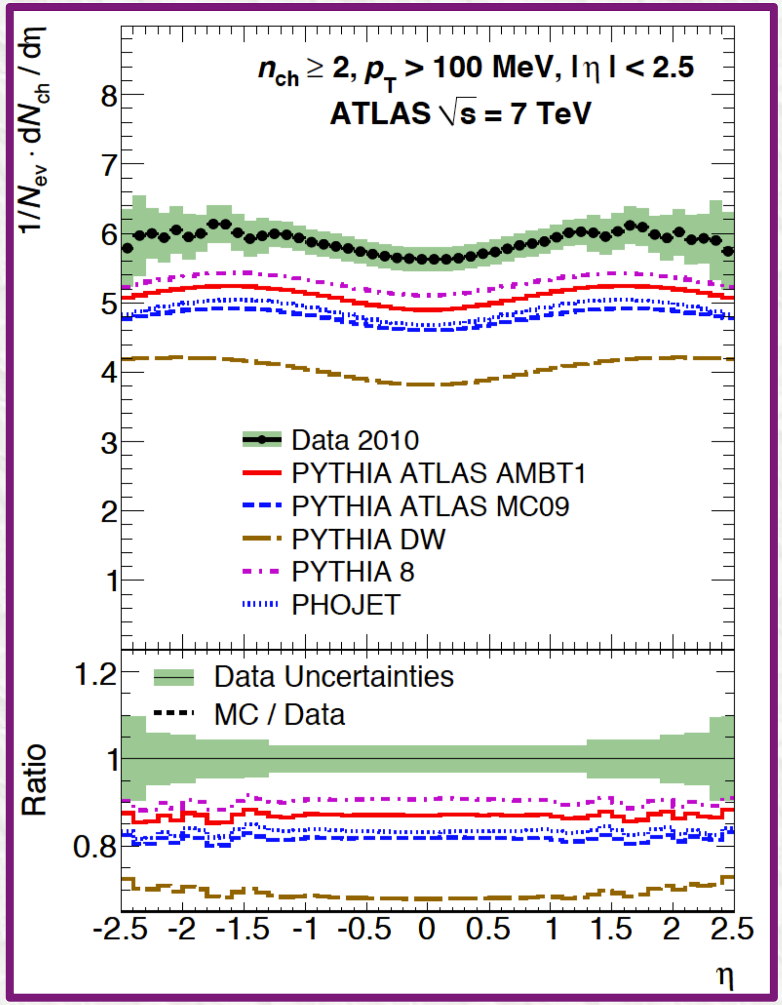
The pre-LHC MC tunes predict lower activity than the data in the transverse region

Charged Particle Multiplicity

CMS: JHEP 01, 079 (2011)



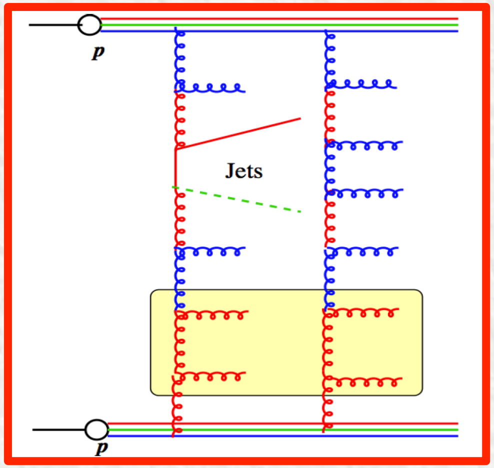
ATLAS: arXiv: 1012.5104



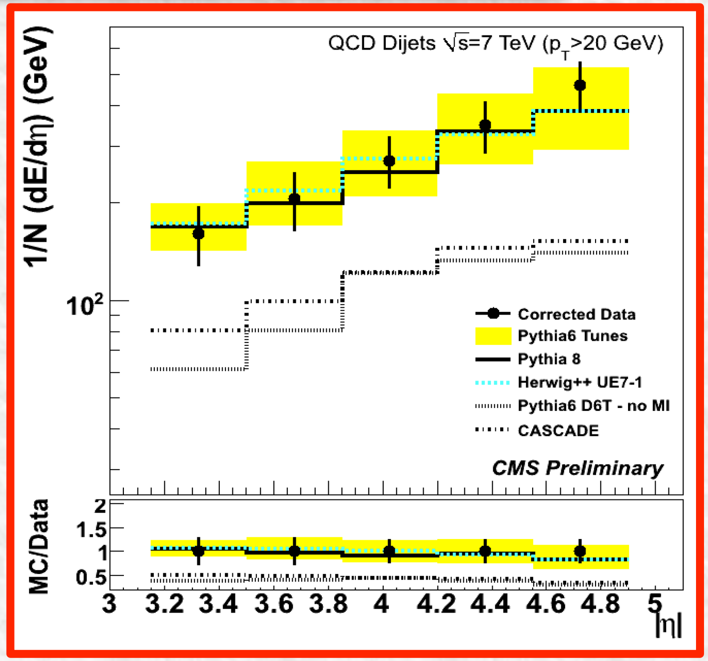
Significant discrepancies with MC models/tunes

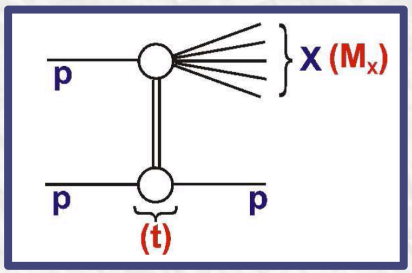
Energy Flow and Diffraction at LHC

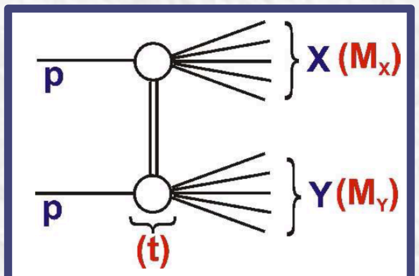
CMS: PAS-FWD-10-011



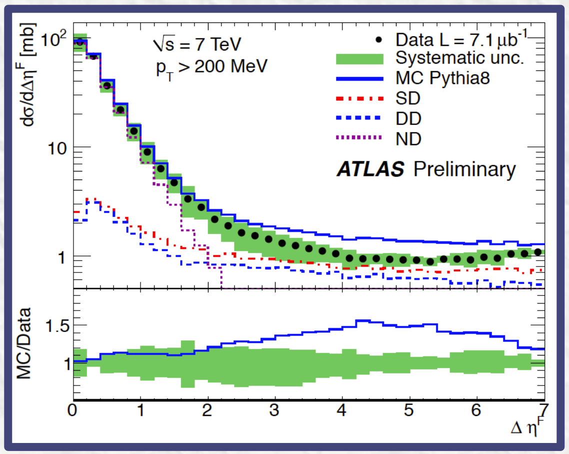
- Use MinBias Events
- Require dijets in central region (p_T>20 GeV, $|\eta|$<2.5)
- Measure energy flow in the forward region 3.15<$|\eta|$<4.9
- Predictions w/o MPI are too low



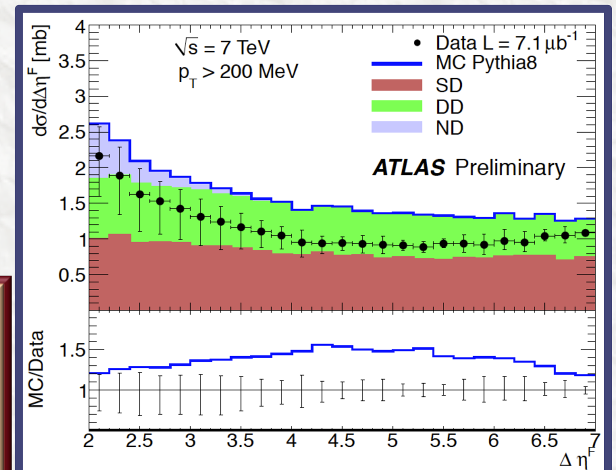


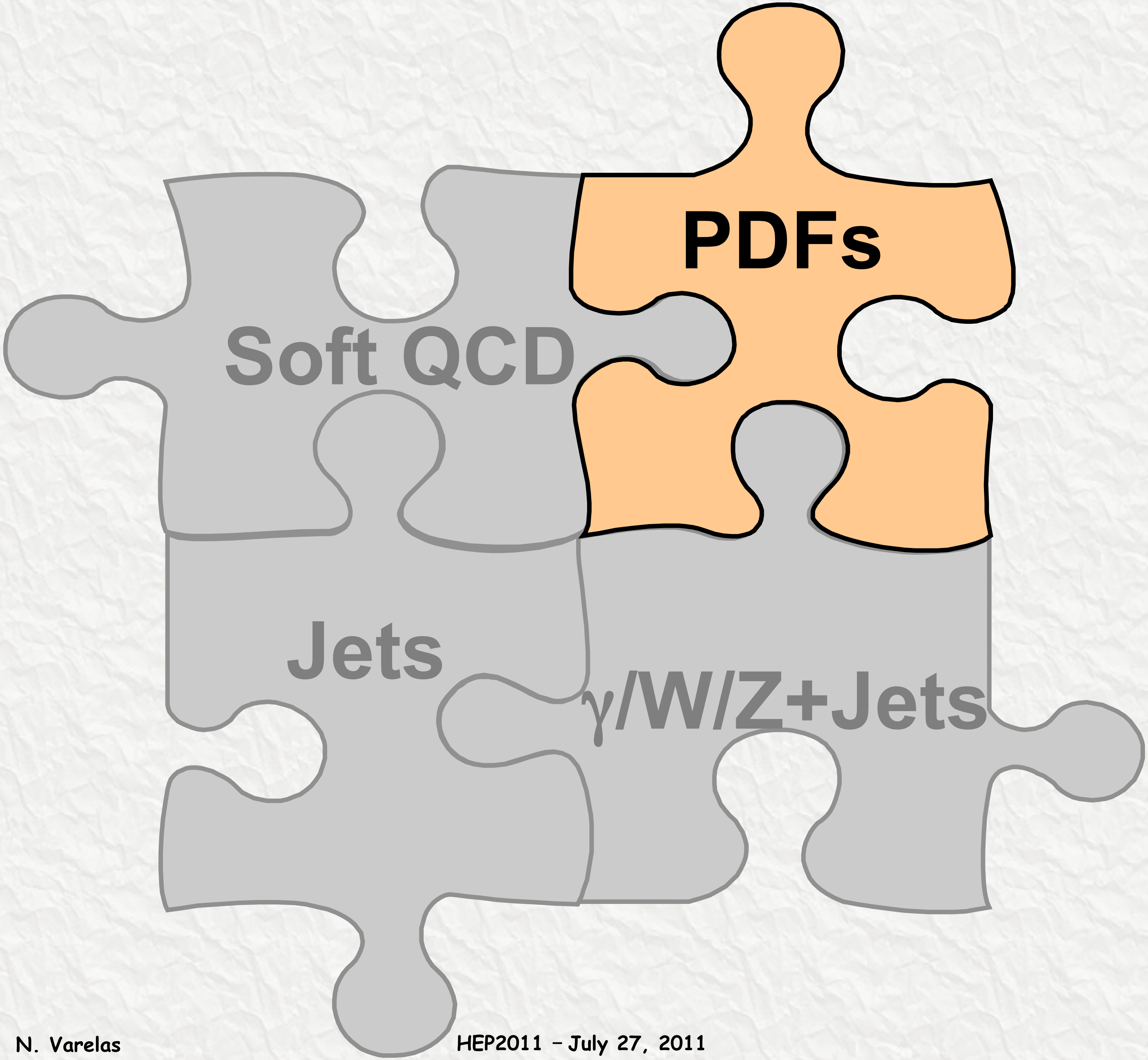


ATLAS: CONF-2011-059



- Rapidity Gap cross section for particles with p_T>200 MeV
- Diffractive fraction is overestimated in the MC




PDFs
Soft QCD
Jets
γ/W/Z+Jets

PDFs

$$d\sigma(h_1h_2 \to cd) = \int_0^1 dx_1 dx_2 \sum_{a,b} f_{a/h_1}(x_1,\mu_F^2) f_{b/h_2}(x_2,\mu_F^2) d\hat{\sigma}^{(ab\to cd)}(Q^2,\mu_F^2)$$

Determine PDFs from global fits to many observables

Input data to MSTW2008 (~2600 points)

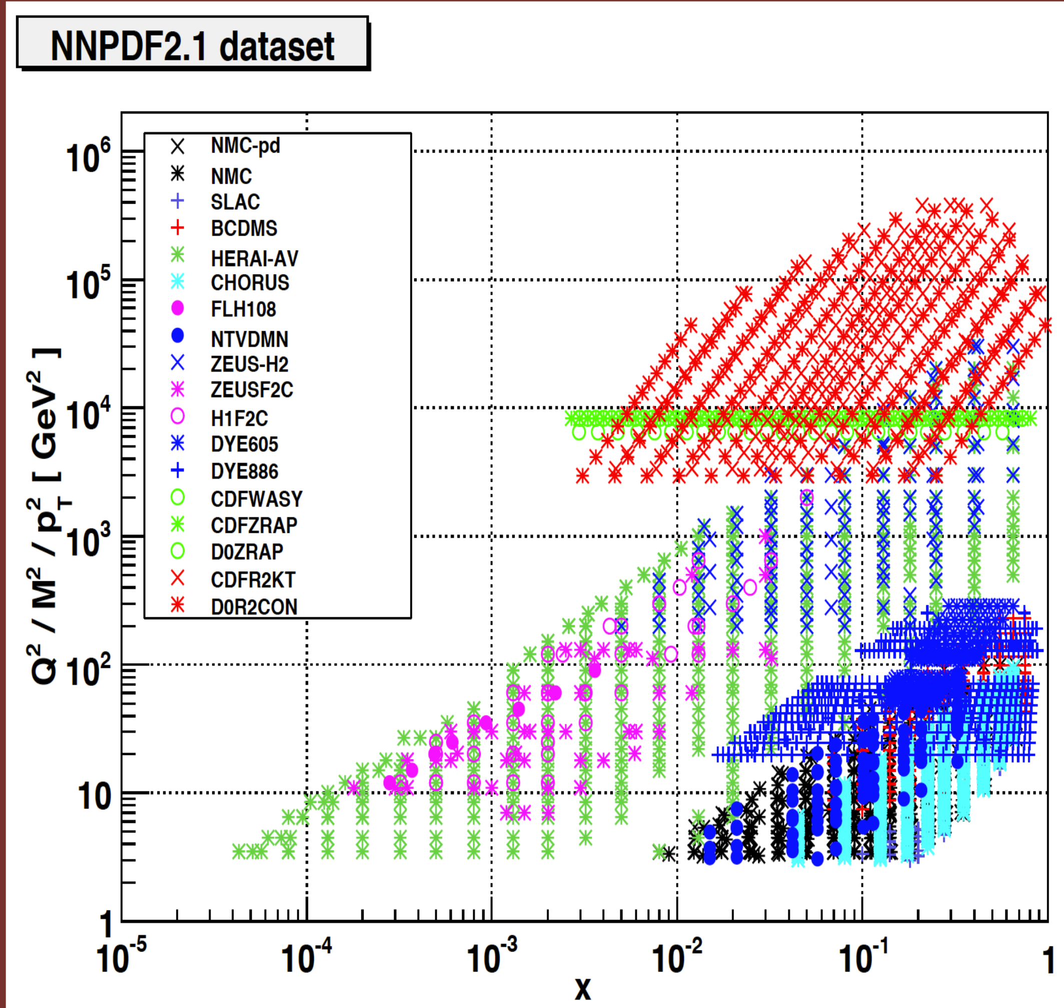
Data set	LO	NLO	NNLO
BCDMS μp F_2 [32]	165 / 153	182 / 163	170 / 163
BCDMS μd F_2 [102]	162 / 142	190 / 151	188 / 151
NMC μp F_2 [33]	137 / 115	121 / 123	115 / 123
NMC μd F_2 [33]	120 / 115	102 / 123	93 / 123
NMC $\mu n/\mu p$ [103]	131 / 137	130 / 148	135 / 148
E665 μp F_2 [104]	59 / 53	57 / 53	63 / 53
E665 μd F_2 [104]	49 / 53	53 / 53	63 / 53
SLAC ep F_2 [105, 106]	24 / 18	30 / 37	31 / 37
SLAC ed F_2 [105, 106]	12 / 18	30 / 38	26 / 38
NMC/BCDMS/SLAC F_L [32–34]	28 / 24	38 / 31	32 / 31
E866/NuSea pp DY [107]	239 / 184	228 / 184	237 / 184
E866/NuSea pd/pp DY [108]	14 / 15	14 / 15	14 / 15
NuTeV νN F_2 [37]	49 / 49	49 / 53	46 / 53
CHORUS νN F_2 [38]	21 / 37	26 / 42	29 / 42
NuTeV νN xF_3 [37]	62 / 45	40 / 45	34 / 45
CHORUS νN xF_3 [38]	44 / 33	31 / 33	26 / 33
CCFR $\nu N \to \mu\mu X$ [39]	63 / 86	66 / 86	69 / 86
NuTeV $\nu N \to \mu\mu X$ [39]	44 / 40	39 / 40	45 / 40
H1 MB 99 e^+p NC [31]	9 / 8	9 / 8	7 / 8
H1 MB 97 e^+p NC [109]	46 / 64	42 / 64	51 / 64
H1 low Q^2 96–97 e^+p NC [109]	54 / 80	44 / 80	45 / 80
H1 high Q^2 98–99 e^-p NC [110]	134 / 126	122 / 126	124 / 126
H1 high Q^2 99–00 e^+p NC [35]	153 / 147	131 / 147	133 / 147
ZEUS SVX 95 e^+p NC [111]	35 / 30	35 / 30	35 / 30
ZEUS 96–97 e^+p NC [112]	118 / 144	86 / 144	86 / 144
ZEUS 98–99 e^-p NC [113]	61 / 92	54 / 92	54 / 92
ZEUS 99–00 e^+p NC [114]	75 / 90	63 / 90	65 / 90
H1 99–00 e^+p CC [35]	28 / 28	29 / 28	29 / 28
ZEUS 99–00 e^+p CC [36]	36 / 30	38 / 30	37 / 30
H1/ZEUS ep F_2^{charm} [41–47]	110 / 83	107 / 83	95 / 83
H1 99–00 e^+p incl. jets [59]	109 / 24	19 / 24	—
ZEUS 96–97 e^+p incl. jets [57]	88 / 30	30 / 30	—
ZEUS 98–00 $e^\pm p$ incl. jets [58]	102 / 30	17 / 30	—
DØ II $p\bar{p}$ incl. jets [56]	193 / 110	114 / 110	123 / 110
CDF II $p\bar{p}$ incl. jets [54]	143 / 76	56 / 76	54 / 76
CDF II $W \to \ell\nu$ asym. [48]	50 / 22	29 / 22	30 / 22
DØ II $W \to \ell\nu$ asym. [49]	23 / 10	25 / 10	25 / 10
DØ II Z rap. [53]	25 / 28	19 / 28	17 / 28
CDF II Z rap. [52]	52 / 29	49 / 29	50 / 29
All data sets	**3066 / 2598**	**2543 / 2699**	**2480 / 2615**

- **DIS (HERA, fixed target)** — NNLO
- **Drell-Yan (Tevatron, fixed target)** — NNLO
- **Vector boson production (Tevatron)** — NNLO
- **Jet Production (Tevatron, HERA)** — NLO
- **Heavy quark production in DIS (HERA)** — NNLO

PDFs

Data used in NNPDF2.1

1



Experiment	Set	Ref.	N_{dat}	x_{min}	x_{max}	Q^2_{min} [GeV^2]	Q^2_{max} [GeV^2]
Deep-Inelastic scattering							
NMC-pd			260 (132)				
	NMC-pd	[32]	260 (132)	0.0015 (0.008)	0.68	0.2 (3.5)	99.0
NMC			288 (221)				
	NMC	[33]	288 (221)	0.0035 (0.009)	0.47	0.8 (3.2)	61.2
SLAC			422 (74)				
	SLACp	[34]	211 (37)	0.07 (0.1)	0.85 (0.55)	0.58 (3.0)	29.2
	SLACd	[34]	211 (37)	0.07 (0.1)	0.85 (0.55)	0.58 (3.2)	29.1
BCDMS			605 (581)				
	BCDMSp	[35]	351 (333)	0.07	0.75	7.5	230.0
	BCDMSd	[36]	254 (248)	0.07	0.75	8.8	230.0
HERAI-AV			741 (592)				
	HERA1-NCep	[23]	528 (379)	$6.2\,10^{-7}$ ($4.3\,10^{-5}$)	0.65	0.045 (3.5)	30000
	HERA1-NCem	[23]	145	$1.3\,10^{-3}$	0.65	90.000	30000
	HERA1-CCep	[23]	34	0.008	0.4	300.0	15000
	HERA1-CCem	[23]	34	0.013	0.4	300.0	30000
CHORUS			1214 (862)				
	CHORUSnu	[37]	607 (431)	0.02 (0.045)	0.65	0.3 (3.0)	95.2
	CHORUSnb	[37]	607 (431)	0.02 (0.045)	0.65	0.3 (3.0)	95.2
FLH108			8				
	FLH108	[38]	8	0.00028	0.0036	12.0	90.000
NTVDMN			90 (79)				
	NTVnuDMN	[39, 40]	45 (41)	0.027	0.36	1.1 (3.1)	116.5
	NTVnbDMN	[39, 40]	45 (38)	0.021	0.25	0.8 (3.1)	68.3
ZEUS-H2			127				
	Z06NC	[41]	90	$5\,10^{-3}$	0.65	200	$3\,10^5$
	Z06CC	[42]	37	0.015	0.65	280	$3\,10^5$
HERA charm structure function data							
ZEUSF2C			69 (50)				
	ZEUSF2C99	[25]	21 (14)	$5\,10^{-5}$ ($3\,10^{-4}$)	0.02	1.8 (7.0)	130
	ZEUSF2C03	[26]	31 (21)	$3\,10^{-5}$ ($1.8\,10^{-5}$)	0.03	2.0 (7.0)	500
	ZEUSF2C08	[27]	9 (7)	$2.2\,10^{-4}$ ($6.5\,10^{-4}$)	0.032	7.0	112
	ZEUSF2C09	[28]	8	$8\,10^{-4}$	0.03	30	1000
H1F2C			47 (38)				
	H1F2C01	[29]	12 (6)	$5\,10^{-4}$	$3.2\,10^{-3}$	1.5 (12)	60
	H1F2C09	[30]	6	$2.4\,10^{-4}$	0.025	120	400
	H1F2C10	[31]	26	$2\,10^{-4}$ ($3.2\,10^{-4}$)	0.05	5.0 (12)	2000
Fixed Target Drell-Yan production							
Experiment	Set	Ref.	N_{dat}	$[y/x^F_{min}, y/x^F_{max}]$	$[x_{min}, x_{max}]$	M^2_{min} [GeV^2]	M^2_{max} [GeV^2]
DYE605			119				
	DYE605	[43]	119	[−0.20, 0.40]	[0.14, 0.65]	50.5	286
DYE866			390				
	DYE866p	[44, 45]	184	[0.0, 0.78]	[0.017, 0.87]	19.8	251.2
	DYE866r	[46]	15	[0.05, 0.53]	[0.025, 0.56]	21.2	166.4
Collider vector boson production							
Experiment	Set	Ref.	N_{dat}	$[y_{min}, y_{max}]$	$[x_{min}, x_{max}]$	M^2_{min} [GeV^2]	M^2_{max} [GeV^2]
CDFWASY			13				
	CDFWASY	[47]	13	[0.10, 2.63]	[$2.9\,10^{-3}$, 0.56]	6463	6463
CDFZRAP			29				
	CDFZRAP	[48]	29	[0.05, 2.85]	[$2.9\,10^{-3}$, 0.80]	8315	8315
D0ZRAP			28				
	D0ZRAP	[49]	28	[0.05, 2.75]	[$2.9\,10^{-3}$, 0.72]	8315	8315
Collider inclusive jet production							
Experiment	Set	Ref.	N_{dat}	$[y_{min}, y_{max}]$	$[x_{min}, x_{max}]$	$p^2_{T,min}$ [GeV^2]	$p^2_{T,max}$ [GeV^2]
CDFR2KT			76				
	CDFR2KT	[50]	76	[0.05, 1.85]	[$4.6\,10^{-3}$, 0.90]	3364	$3.7\,10^5$
D0R2CON			110				
	D0R2CON	[51]	110	[0.20, 2.20]	[$3.1\,10^{-3}$, 0.97]	3000	$3.4\,10^5$
Total							
Experiment			N_{dat}	x_{min}	x_{max}	Q^2_{min} [GeV^2]	Q^2_{max} [GeV^2]
TOTAL			4520 (3415)	$3.1\,10^{-5}$	0.97	2.0	$3.7\,10^5$

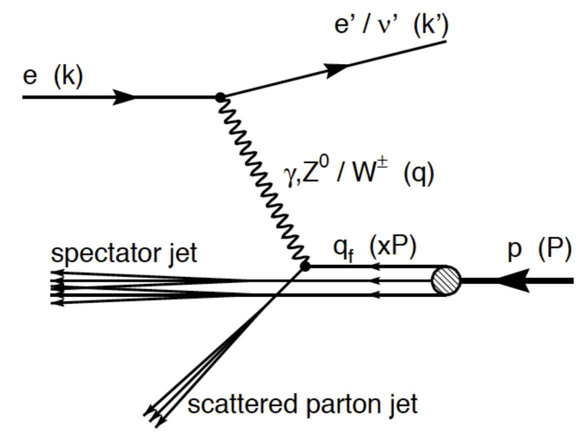
PDF Families

- **MSTW: (DIS+DY+Jets+W/Z, LO/NLO/NNLO)** (Martin, Stirling, Thorne, Watt)
  - **MRS→…→MSTW2008** **arXiv: 0901.0002**
  - http://projects.hepforge.org/mstwpdf/
- **CTEQ: (DIS+DY+Jets+W/Z, LO/NLO)** (Lai, Guzzi, Huston, Li, Nadolsky, Pumplin, Yuan)
  - **CTEQ→…→CT10** **arXiv: 1106.5788**
  - http://www.phys.psu.edu/~cteq/#PDFs
- **NNPDF: (DIS+DY+Jets+W/Z, NLO)** (Ball, Bertone, Cerutti, Del Debbio, Forte, Guffanti, Latorre, Rojo, Ubiali)
  - **NNPDF1.0→…→NNPDF2.1** **arXiv: 1101.1300**
  - http://sophia.ecm.ub.es/nnpdf/
- **JR09: (DIS+DY+Jets, NNLO)** (Jiminez-Delgado, Reya) **arXiv: 0810.4274**
  - **GJR08: (LO/NLO)** (Glück, Jiminez-Delgado, Reya) **arXiv: 0709.0614**
  - http://durpdg.dur.ac.uk/hepdata/grv.html
- **ABKM09: (DIS+DY, NLO/NNLO)** (Alekhin, Blümlein, Klein, Moch) **arXiv:0908.2766**
  - https://mail.ihep.ru/~alekhin/abkm09/abkm09.html
- **HERAPDF1.0→1.7** (v1.5 w/ HERA II DIS data, v1.7+H1/ZEUS jets+F2cc): (NLO/NNLO)
  - https://www.desy.de/h1zeus/combined_results/herapdftable **arXiv: 0911.0884**

The Les Houches Accord PDF Interface → http://projects.hepforge.org/lhapdf/

DIS @ HERA

$$\sigma_r^{\pm} \equiv \frac{d^2\sigma_{NC}^{e^\pm p}}{dxdQ^2}\frac{xQ^4}{2\pi\alpha^2}\frac{1}{Y_+} = F_2 - \frac{y^2}{Y_+}F_L \mp \frac{Y_-}{Y_+}xF_3$$



$$F_2(x,Q^2) = x\sum A_i\left(q_i + \bar{q}_i\right)$$

quark distributions

gluon from scaling violations

From scaling violations:
$F_L \sim \alpha_s xg(x,Q^2)$

$$xF_3(x,Q^2) = x\sum B_i\left(q_i - \bar{q}_i\right)$$

Extracted from $\sigma_{NC}^{e^+p} - \sigma_{NC}^{e^-p}$

valence PDFs

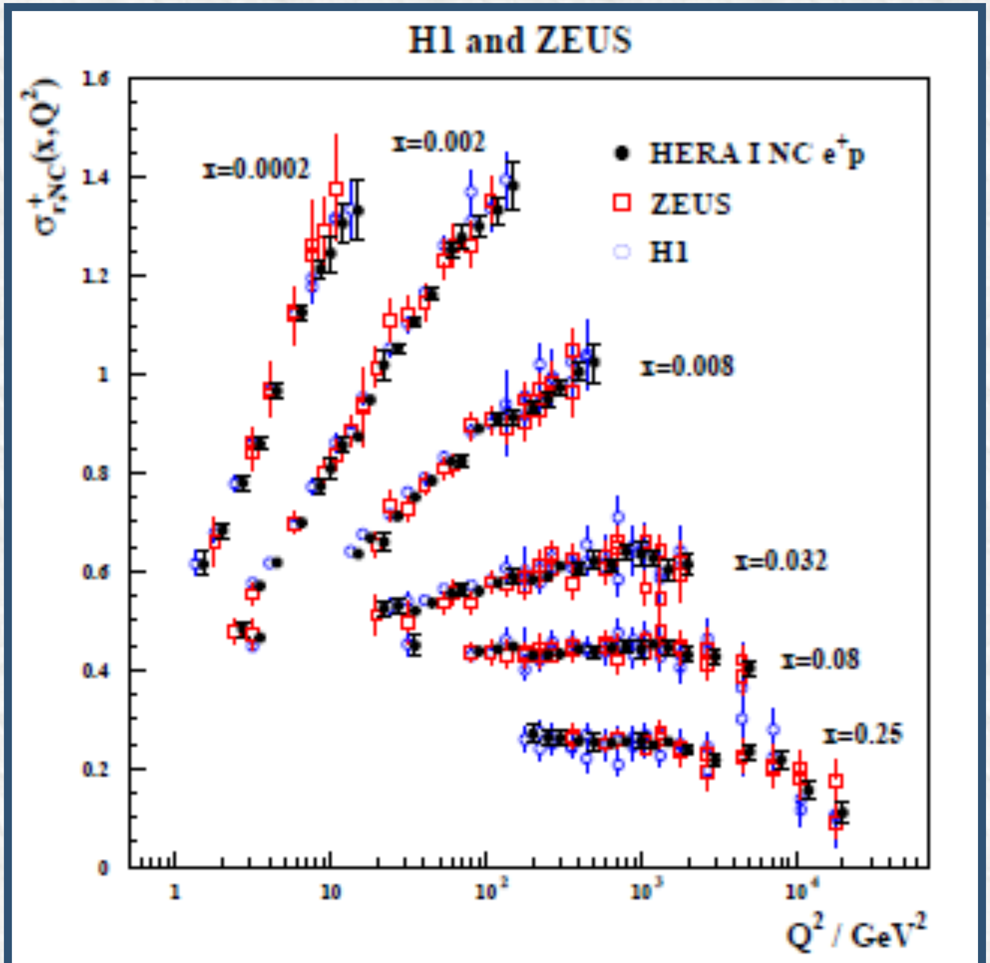
$$Q^2 = -q^2 = -(k' - k)^2$$
$$y = \frac{P\cdot q}{P\cdot k}$$
$$x = \frac{Q^2}{2P\cdot q} \quad \text{(Bjorken)}$$

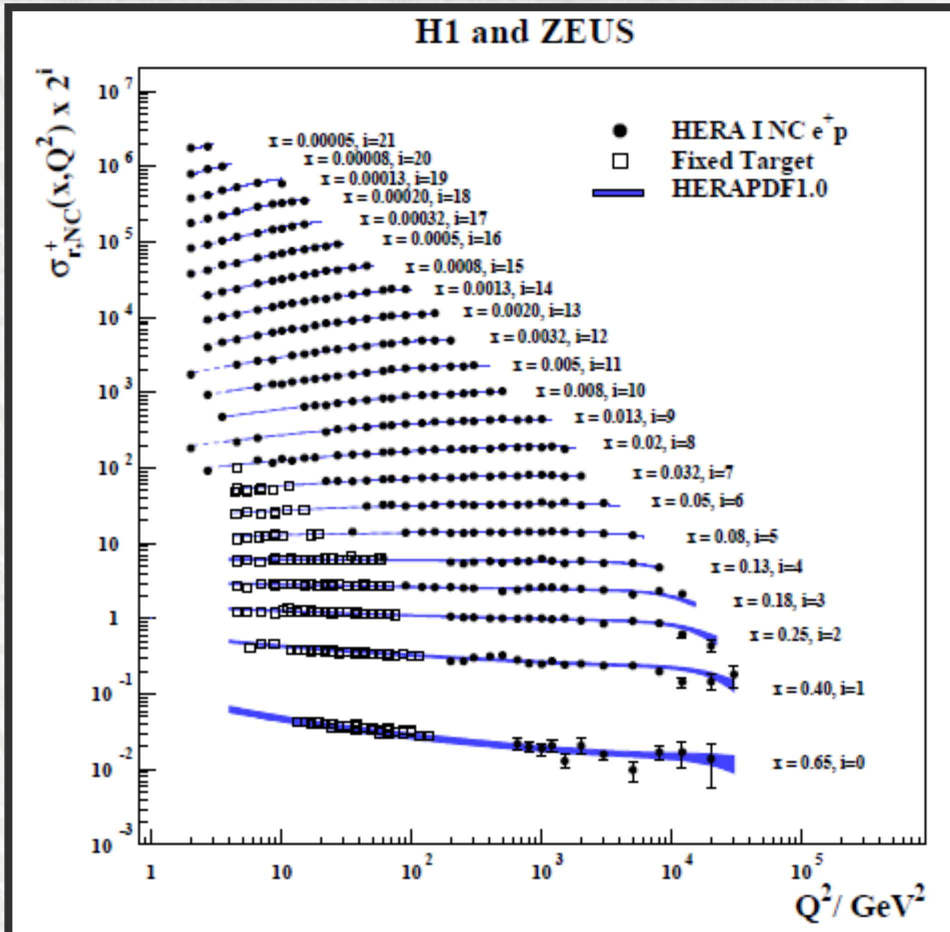
$$Y_\pm = 1 \pm (1-y)^2$$

CC: Probes flavor structure of the proton

$$\sigma_{r,CC} \equiv \frac{2\pi x}{G_F^2}\left[\frac{M_W^2 + Q^2}{M_W^2}\right]^2 \frac{d^2\sigma_{CC}}{dxdQ^2} = \begin{cases} (x\bar{u} + x\bar{c}) + (1-y^2)(xd + xs) & \text{for } e^+p \\ (xu + xc) + (1-y^2)(x\bar{d} + x\bar{s}) & \text{for } e^-p \end{cases}$$

ZEUS-H1 Combined Results



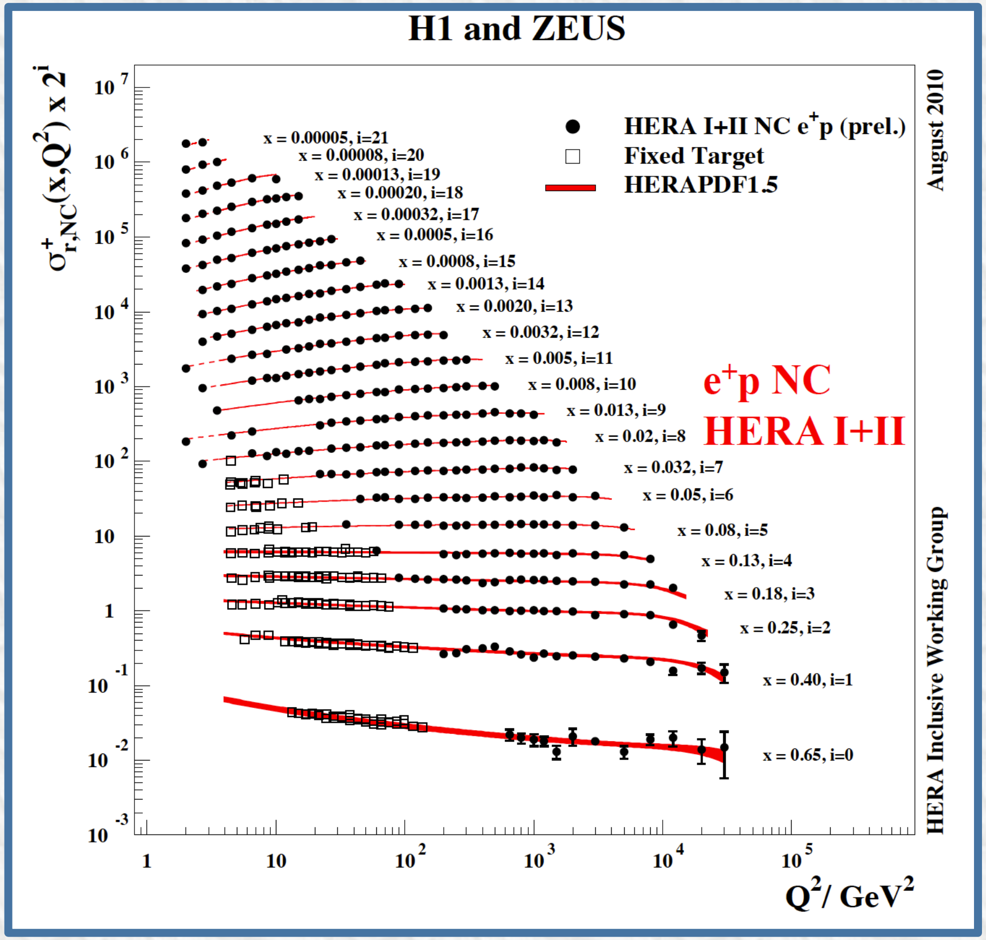


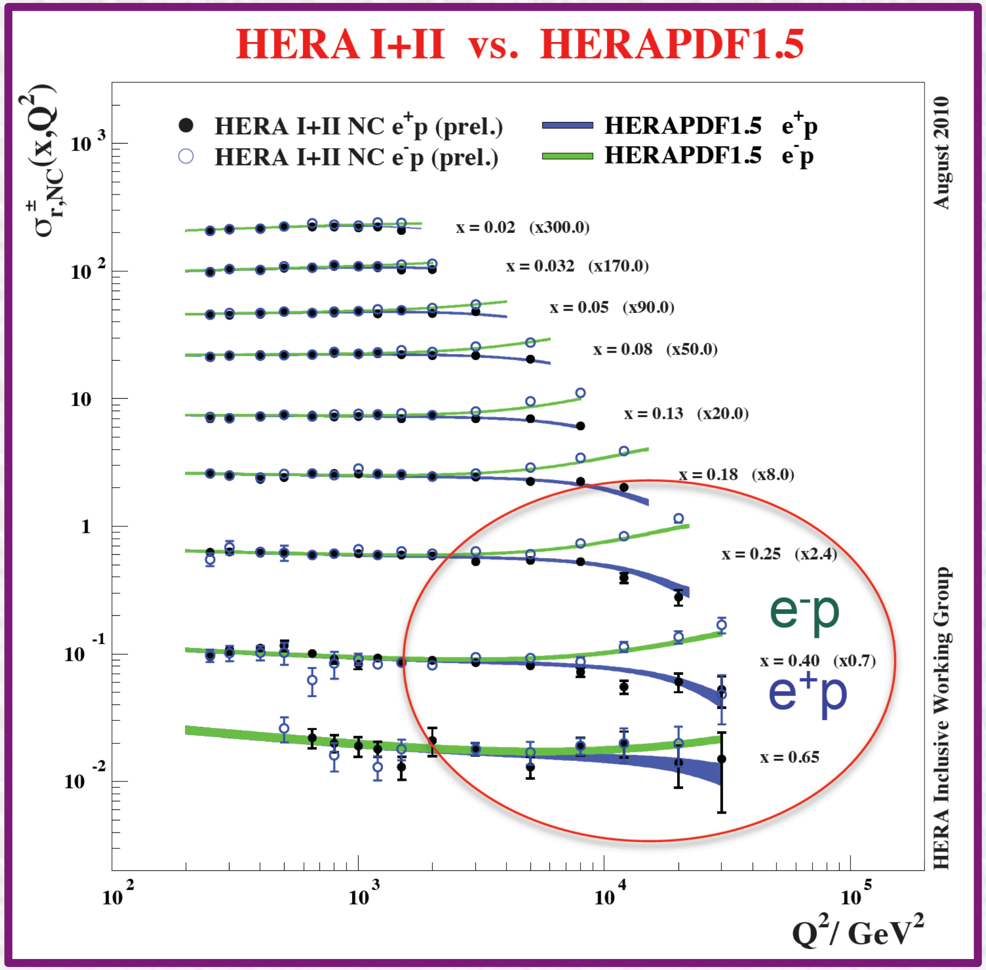
Combined H1-ZEUS data reduce uncertainties

Combined H1-ZEUS inclusive data HERAPDF fits work well

H1 & ZEUS: JHEP 1001:109 (2010)

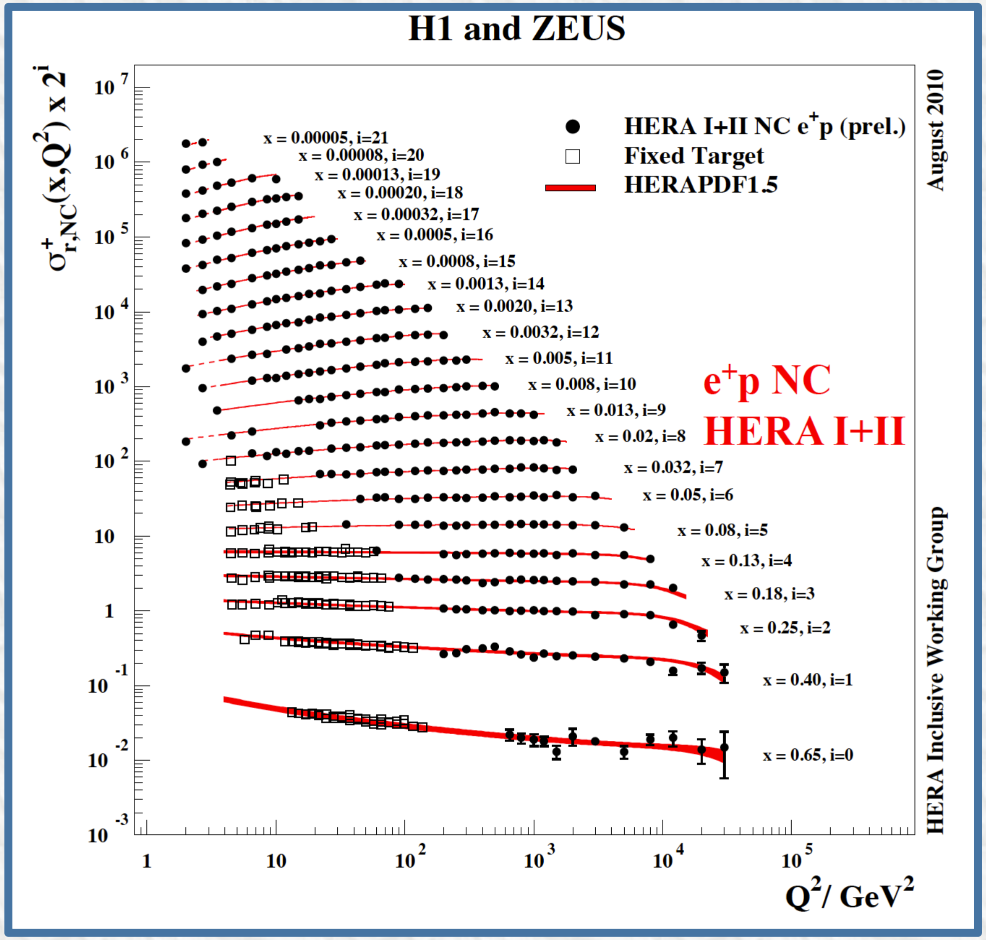
HERA I+II Combined Results

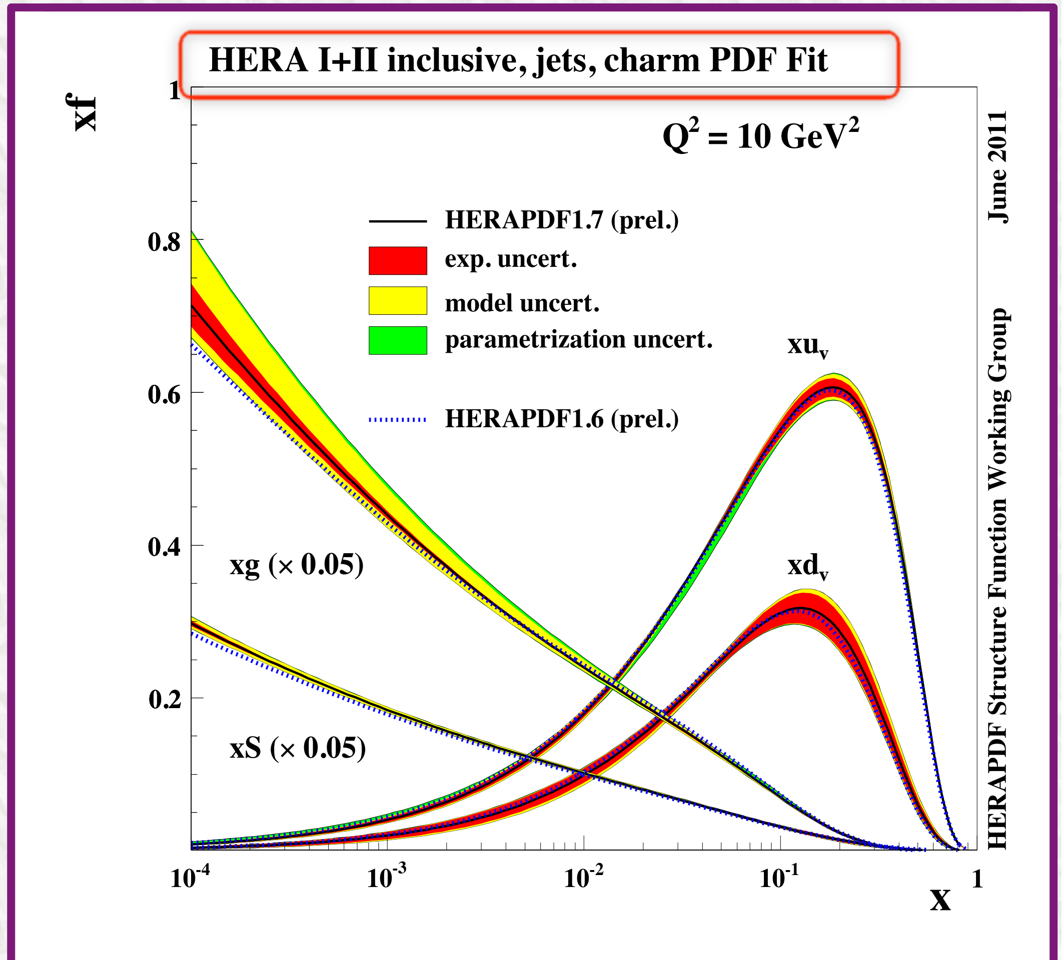




Combined HERA I+II inclusive data → HERAPDF1.5

HERA I+II Combined Results





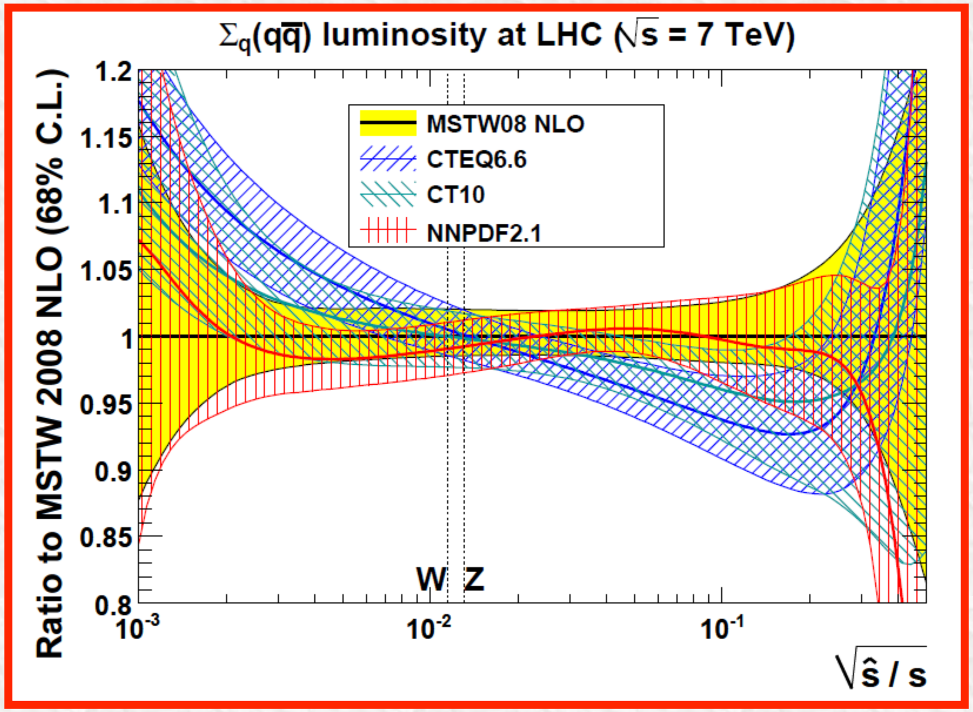
Combined HERA I+II inclusive data → HERAPDF1.5

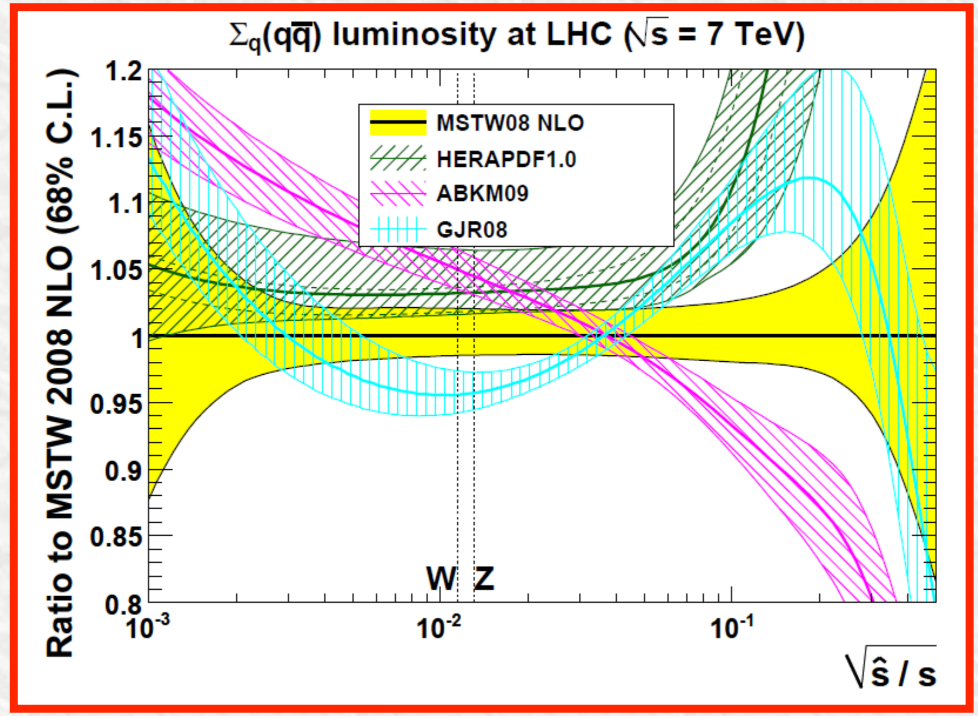
HERAPDF1.7 vs. 1.6

How Do PDFs Compare?

$$\frac{\partial \mathcal{L}_{\Sigma_q(q\bar{q})}}{\partial \hat{s}} = \frac{1}{s}\int_\tau^1 \frac{\mathrm{d}x}{x} \sum_{q=d,u,s,c,b} \left[f_q(x,\hat{s}) f_{\bar{q}}(\tau/x,\hat{s}) + f_{\bar{q}}(x,\hat{s}) f_q(\tau/x,\hat{s})\right]$$

G. Watt: arXiv:1106.5788





- Variations among sets (differences in data samples, value/uncertainties of α_s, treatment of heavy quarks, initial parametrizations,...)
- Tevatron high-p_T jets affect the high-x gluon distribution
- The new LHC results on W/Z production, W asymmetry, Z rapidity distribution, photons… will help to further constrain the PDFs

How Do PDFs Compare?

$$\frac{\partial \mathcal{L}_{gg}}{\partial \hat{s}} = \frac{1}{s} \int_{\tau}^{1} \frac{\mathrm{d}x}{x} \, f_g(x, \hat{s}) f_g(\tau/x, \hat{s})$$

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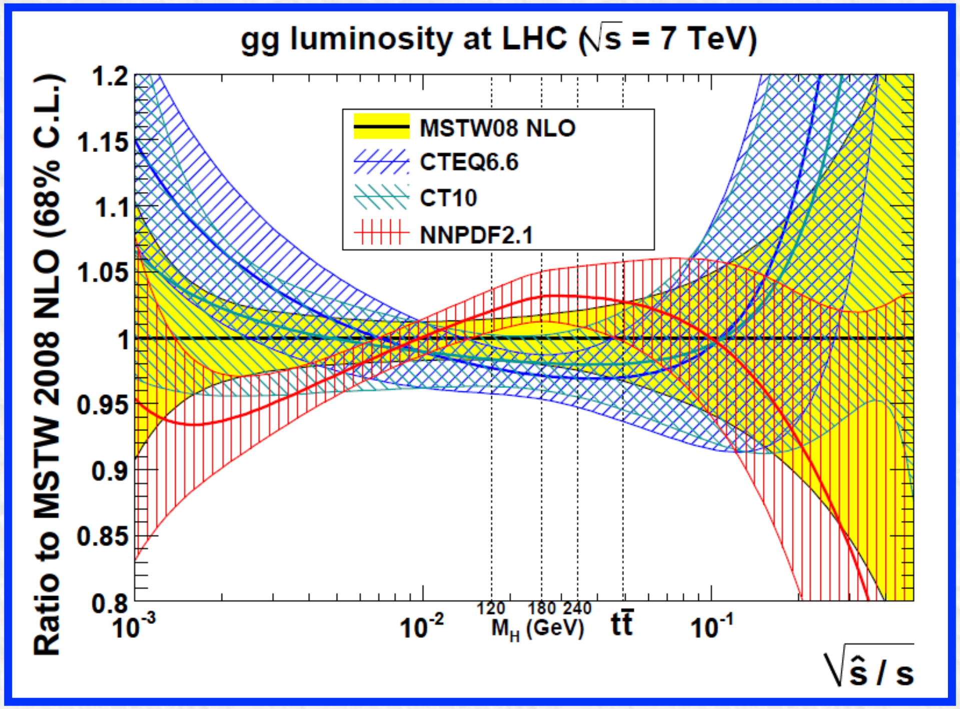

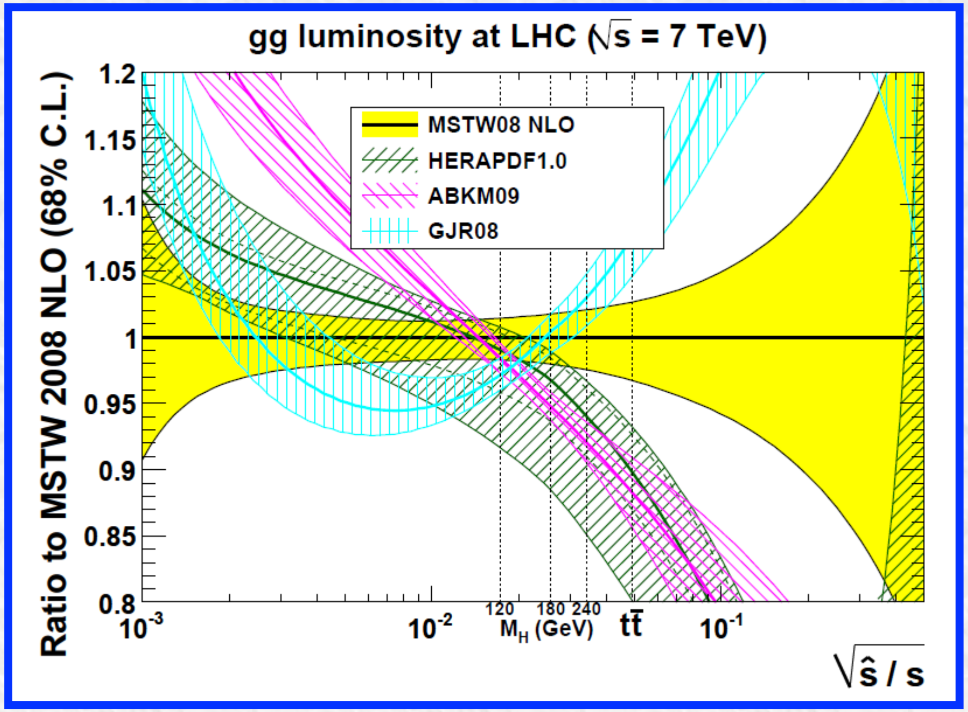

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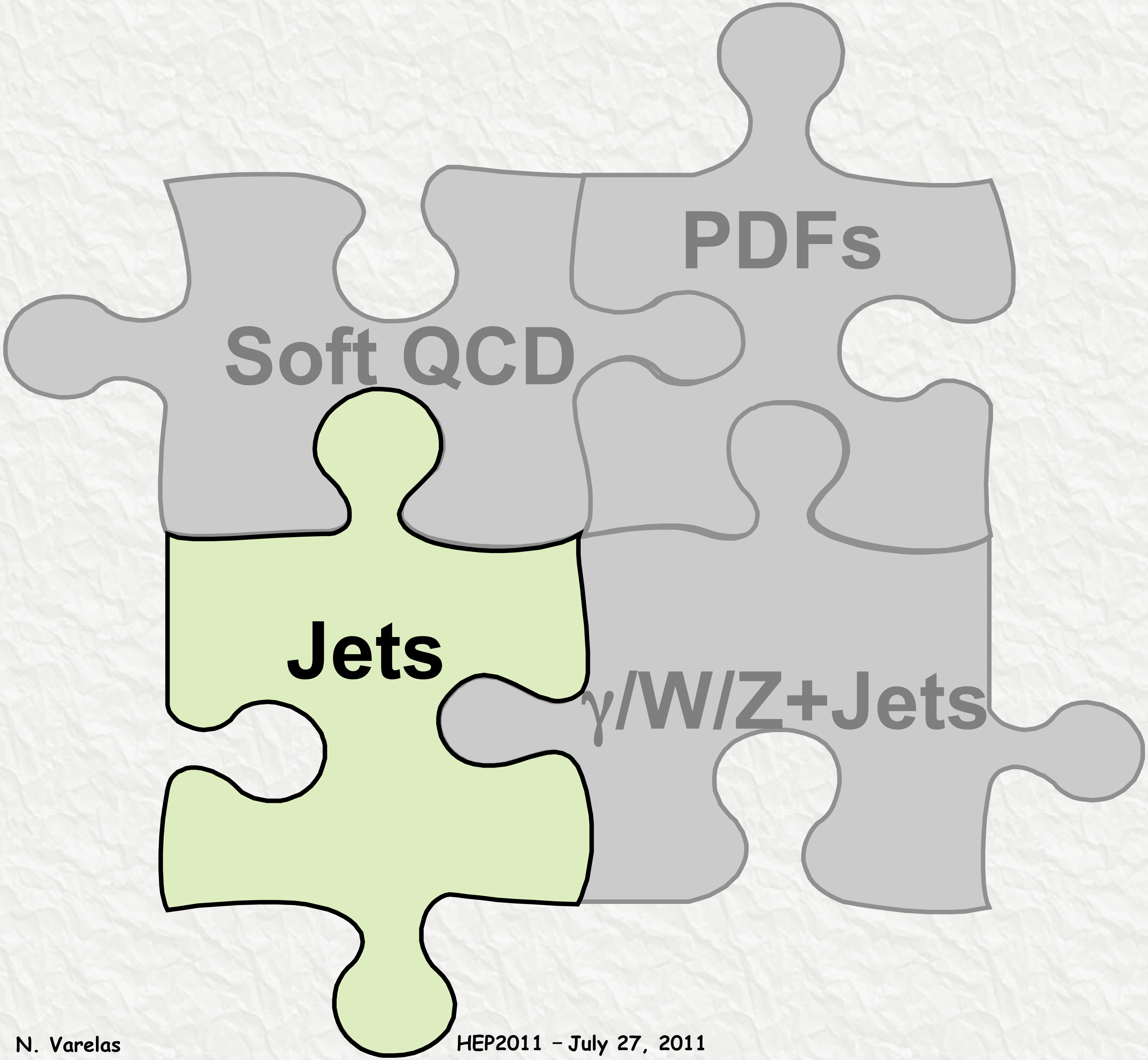

PDFs
Soft QCD
Jets
γ/W/Z+Jets

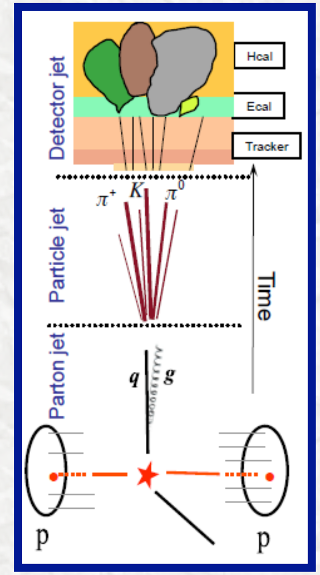
Jet Algorithms

- **Clustering algorithms:**
  - **Cone algorithms:**
    - Iterative Cone, Snowmass, and other Legacy algorithms
    - Midpoint (Tevatron Run-II)
    - Seedless Infrared Safe Cone (SISCone)
  - **Recombination algorithms:**
    - p=1 → k_T jet algorithm
    - p=0 → Cambridge/Aachen jet algorithm
    - p=-1 → "Anti-k_T" jet algorithm → default algorithm for ***ATLAS & CMS***
      - Soft particles will first cluster with hard particles before among themselves
      - Almost a cone jet near hard partons

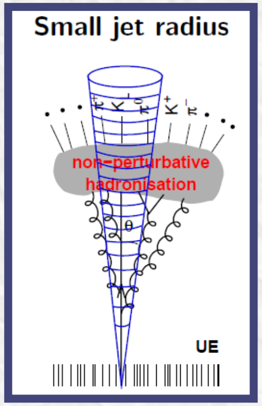
$$d_{ij} = \min\left(p_{Ti}^{2p}, p_{Tj}^{2p}\right)\frac{\Delta R_{ij}^2}{R^2}$$

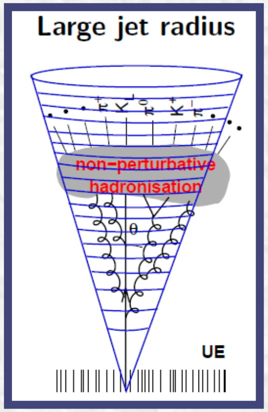
$$d_{ii} = p_{Ti}^{2p}$$

$$\Delta R_{ij}^2 = \left(y_i - y_j\right)^2 + \left(\phi_i - \phi_j\right)^2$$

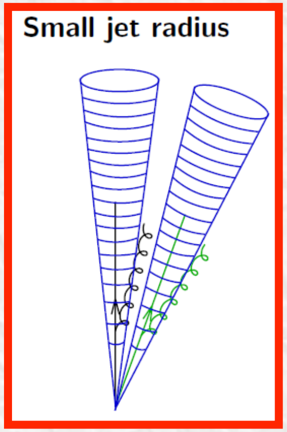


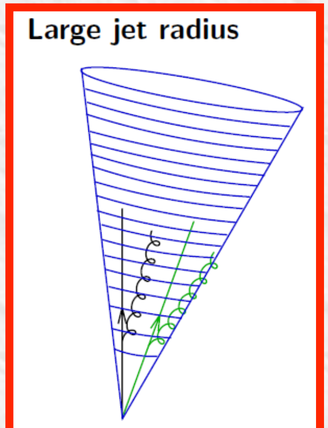
- **Sensitivity to clustering radius**





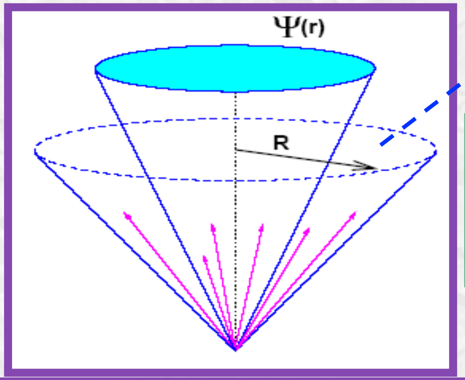
Salam





Jet Substructure

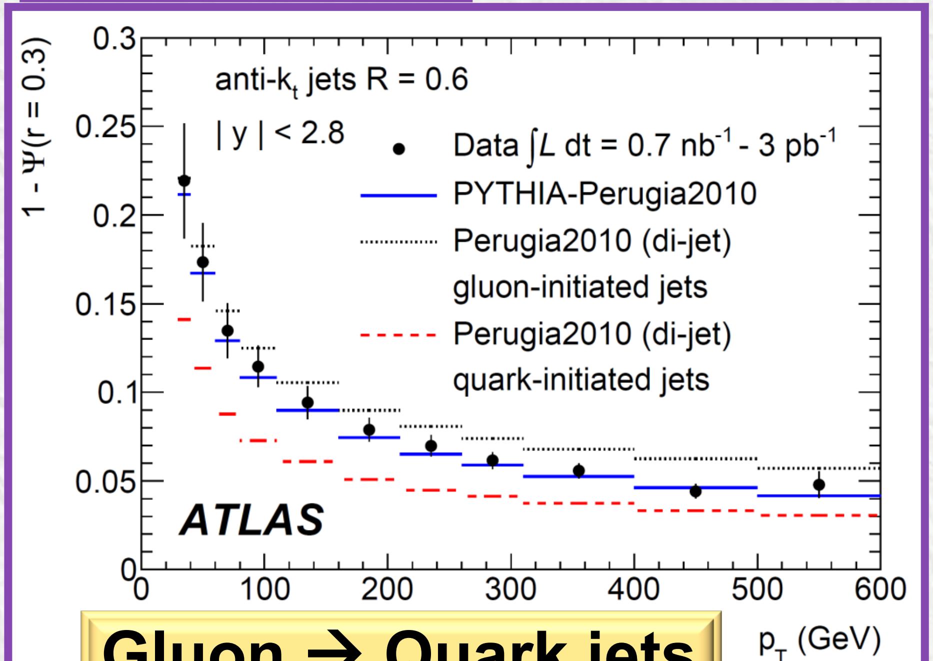
Integrated Jet Shape: average fraction of jet transverse momentum that lies inside a cone of radius r concentric to the jet axis



1-Ψ(r)

$$\Psi(r) = \frac{1}{N_{jets}} \sum_{jets} \frac{p_T(0,r)}{p_T(0,R)}$$

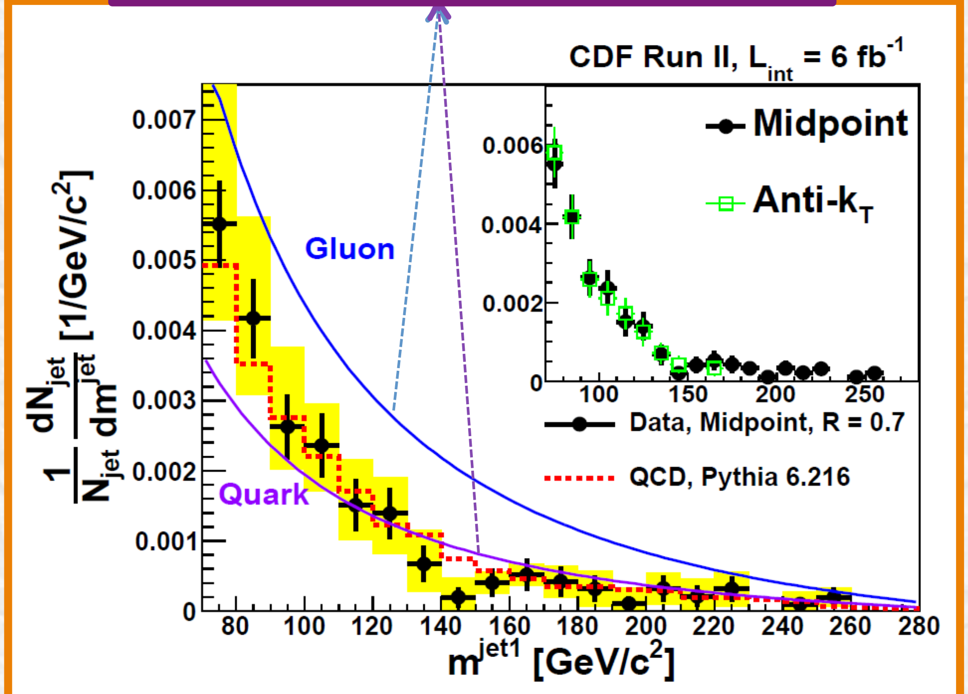
ATLAS: PRD 83, 052003 (2011)



Gluon → Quark jets

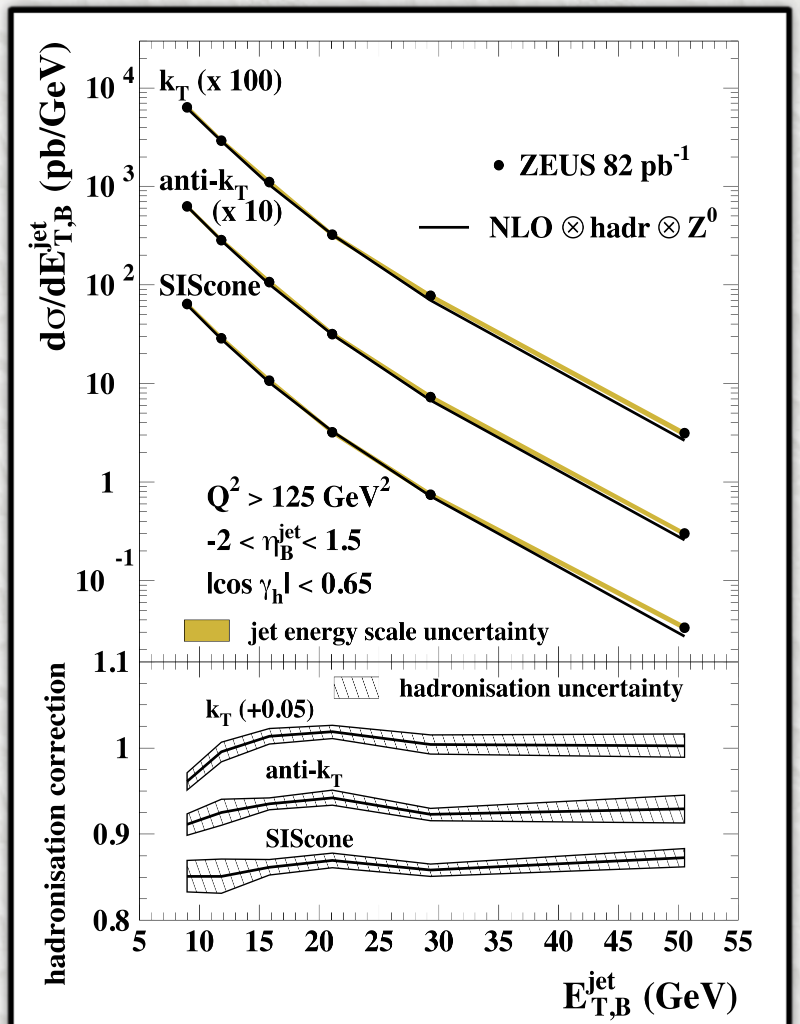
- Jet Mass Distribution for jets with p_T > 400 GeV
- Midpoint and Anti-k_T Jets
- Comparison to Pythia + NLO Jet Function for quarks/gluons

$$J(m^{jet}, p_T, R) \simeq \alpha_s(p_T) \frac{4\, C_{q,g}}{\pi m^{jet}} \log\left(\frac{R \cdot p_T}{m^{jet}}\right)$$

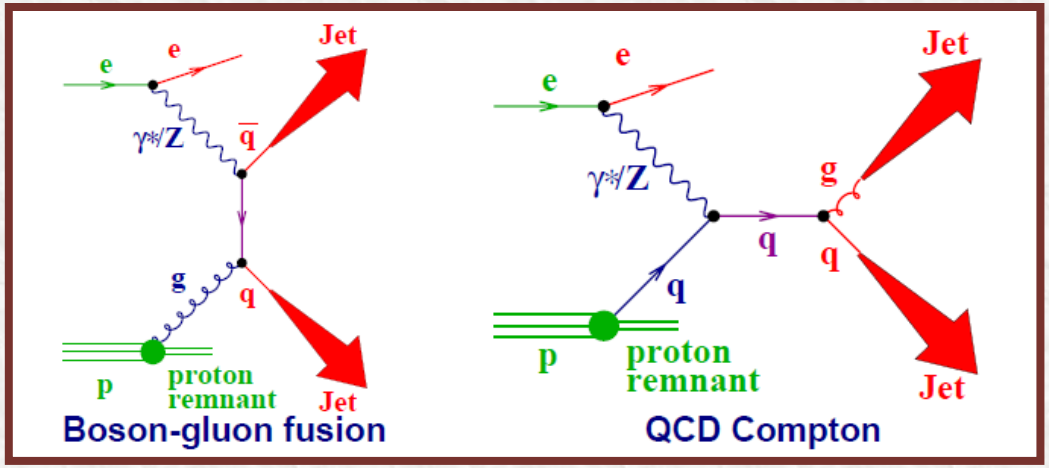


CDF: arXiv:1106.5952

Jet Production in DIS at HERA



ZEUS: PLB 691, 127 (2010)

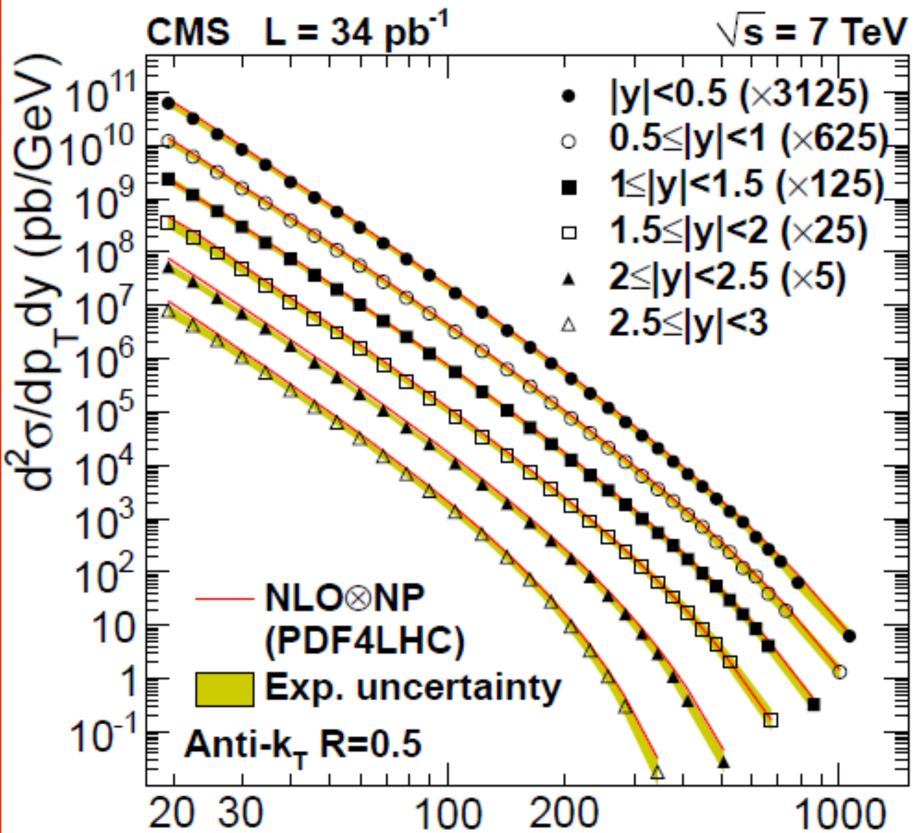


Larger hadronization corrections for SISCone than anti-k_T & k_T

Good agreement with NLO QCD

Jet & Dijet Cross Sections at LHC

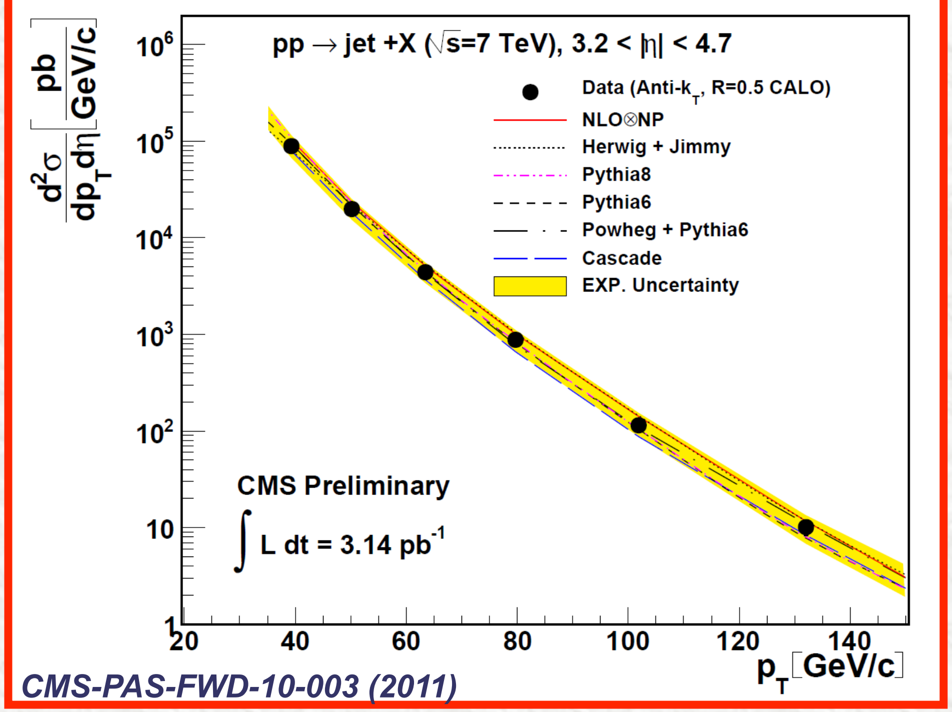
- Inclusive Jet Cross Section
- Comparisons to NLO×NP



CMS: arXiv:1106.0208

Jet & Dijet Cross Sections at LHC

- Inclusive Jet Cross Section
- Comparisons to NLO×NP

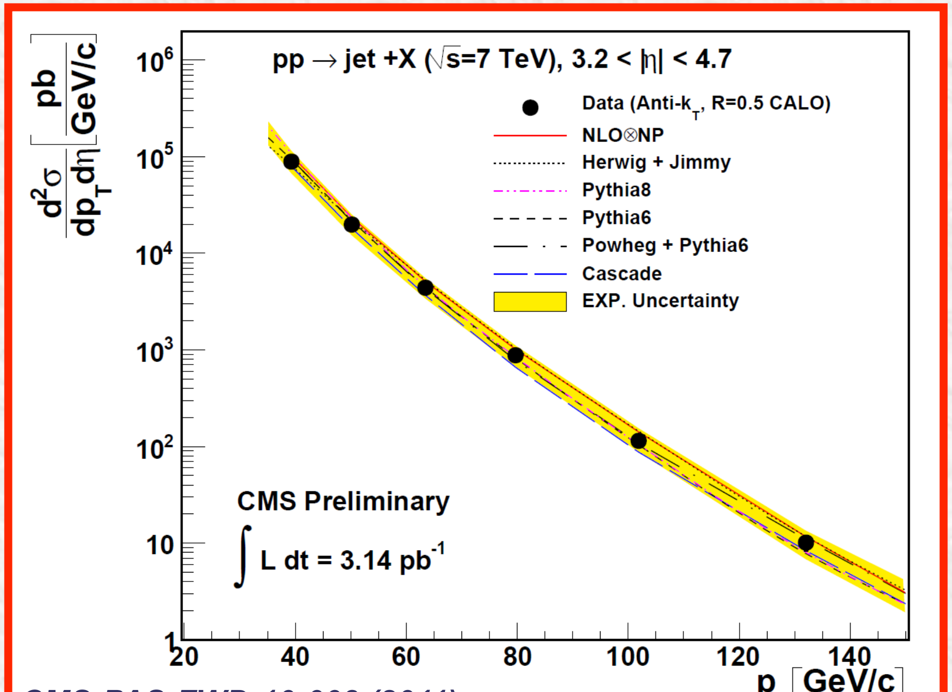


CMS-PAS-FWD-10-003 (2011)

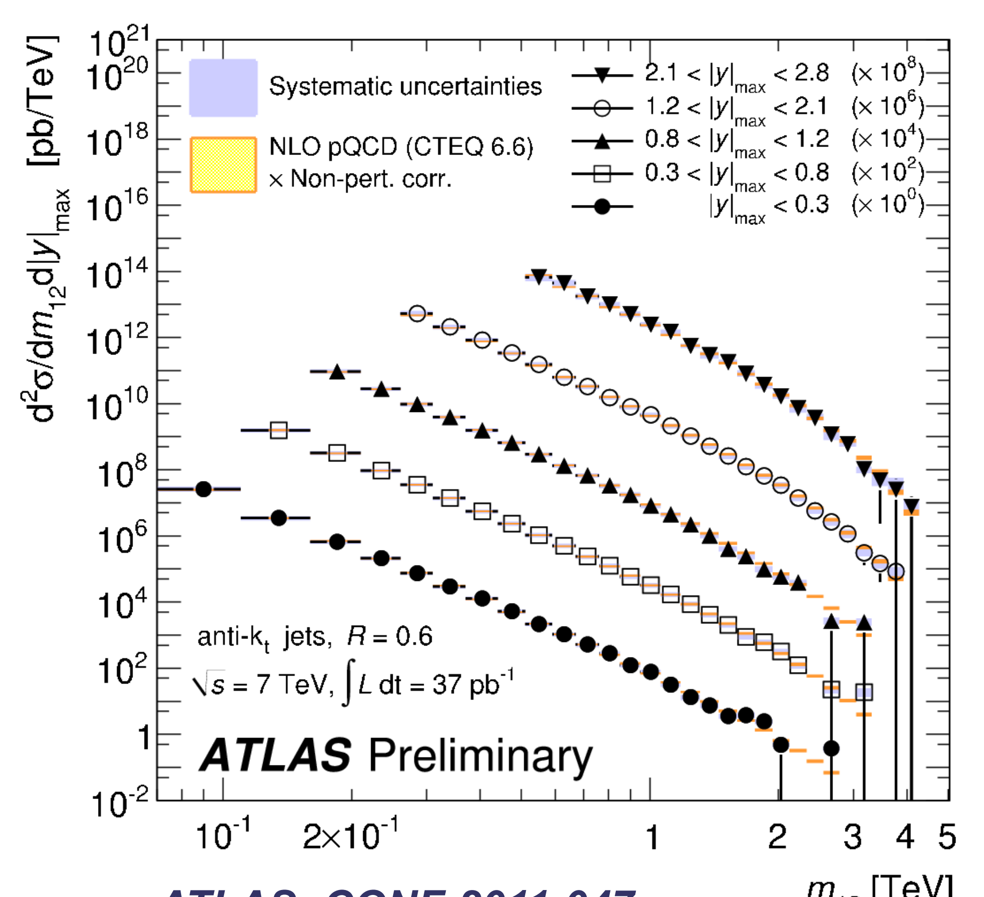
Jet & Dijet Cross Sections at LHC

- Inclusive Jet Cross Section
- Comparisons to NLO×NP

- Dijet Mass Cross Section
- Comparisons to NLO×NP



CMS-PAS-FWD-10-003 (2011)

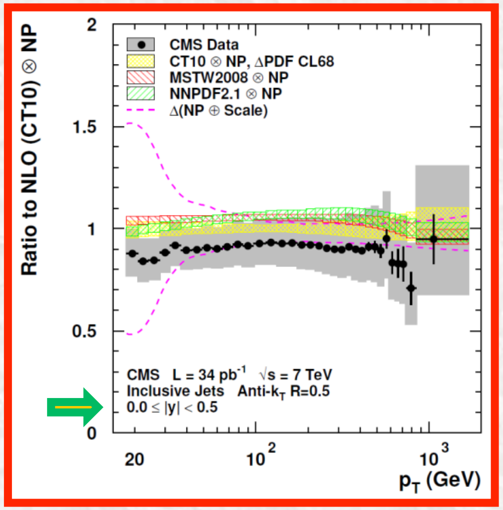


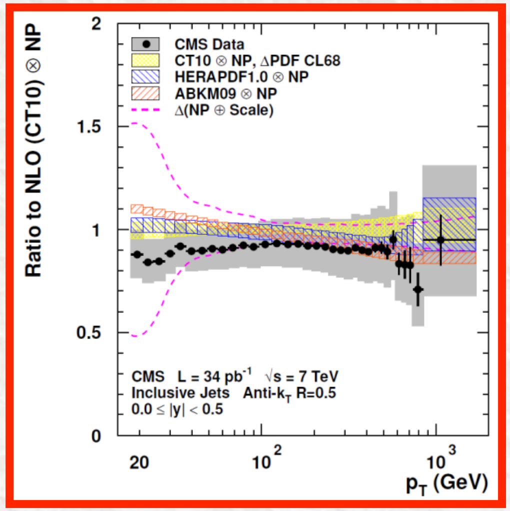
ATLAS: CONF-2011-047

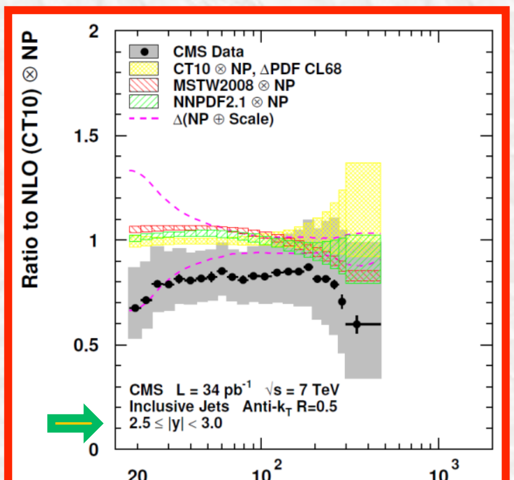
Jet Production: Data vs Theory

- Inclusive Jet Cross Section
- Data/Theory (NLO×NP)

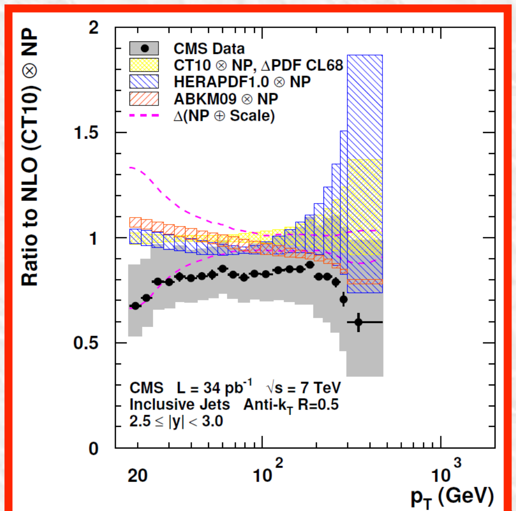
- Dijet Mass Cross Section
- Data/Theory (NLO×NP)

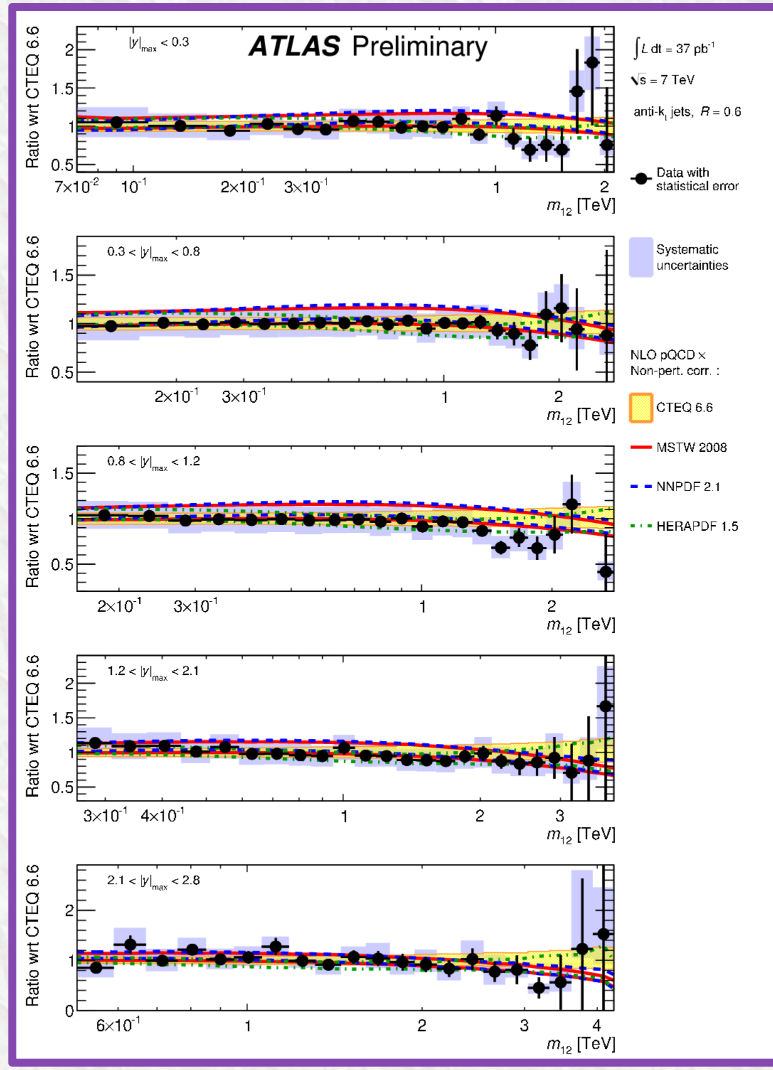






CMS-Note 004 (2011)

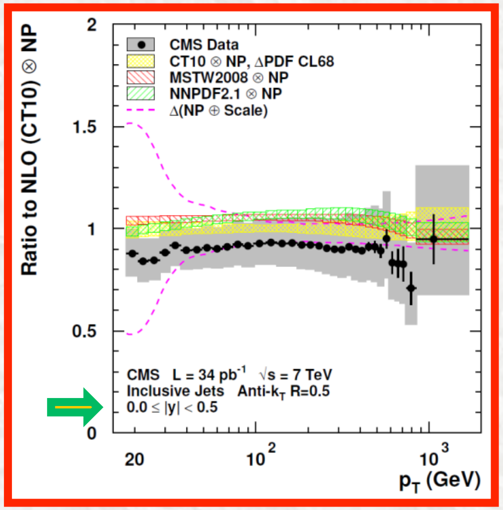


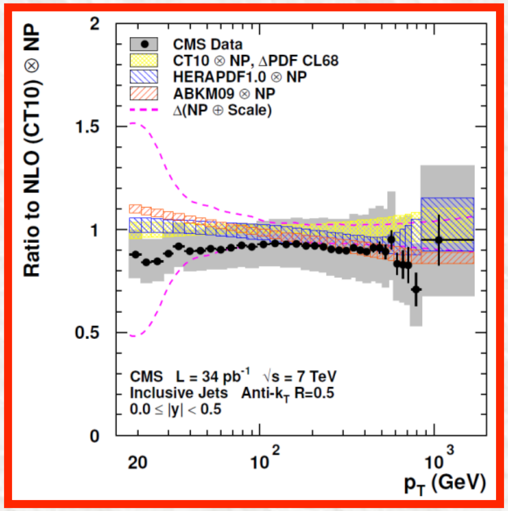


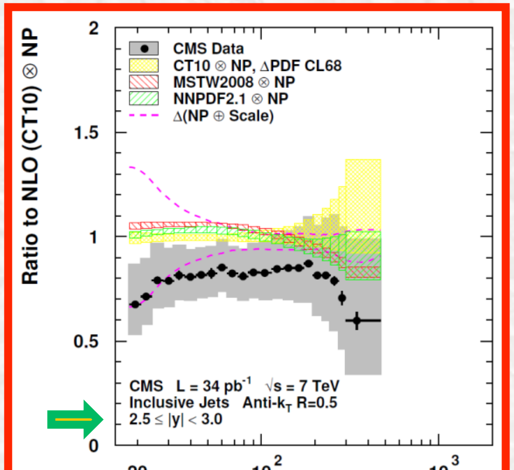
Jet Production: Data vs Theory

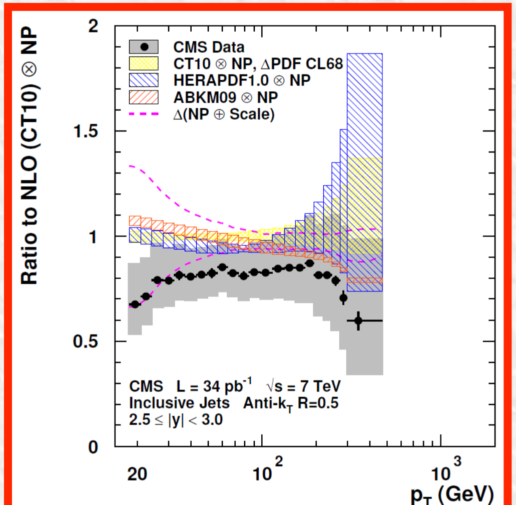
- Inclusive Jet Cross Section
- Data/Theory (NLO×NP)

- Dijet Mass Cross Section
- Data/Theory (POWHEG+Pythia/Herwig)

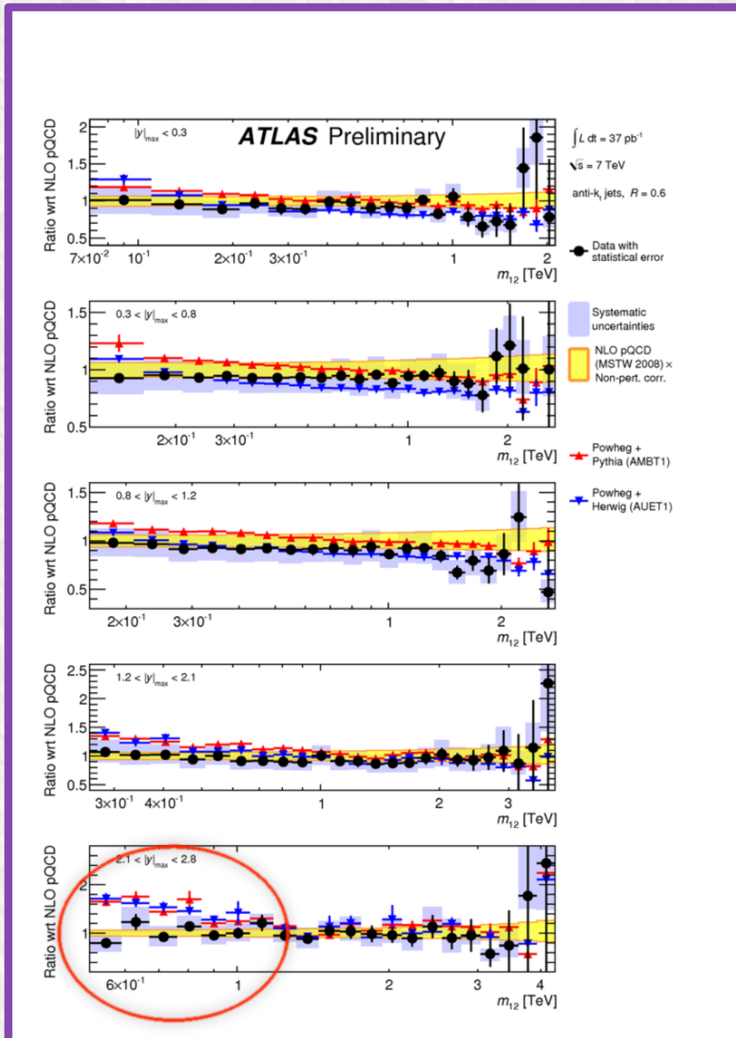




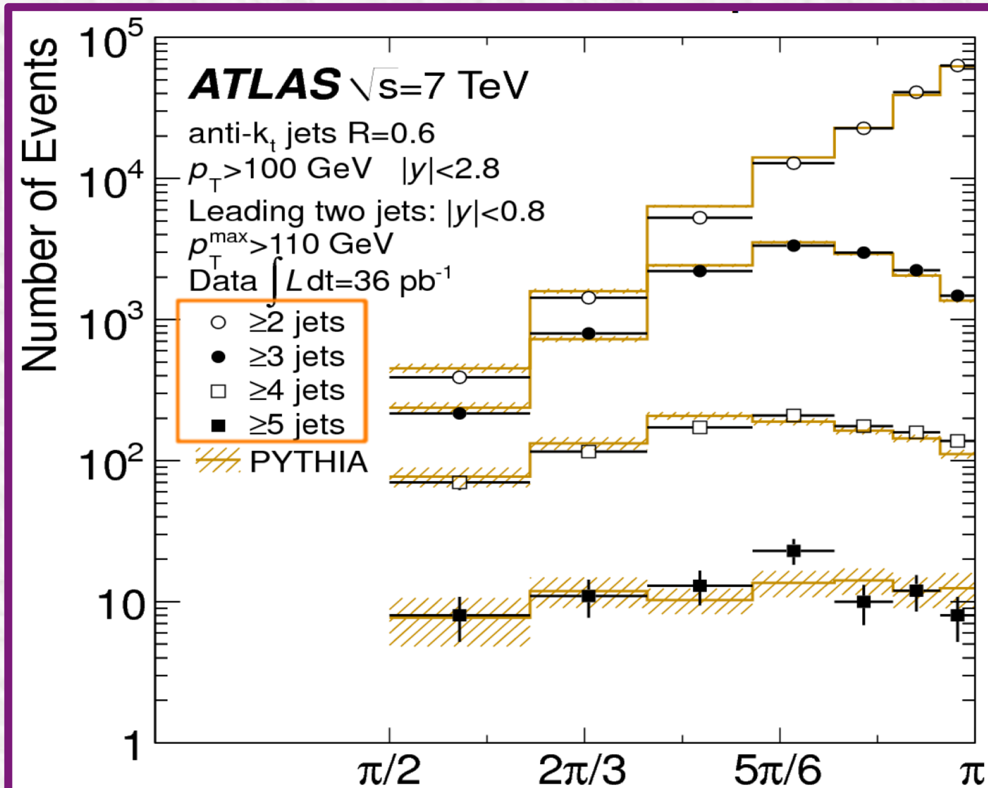




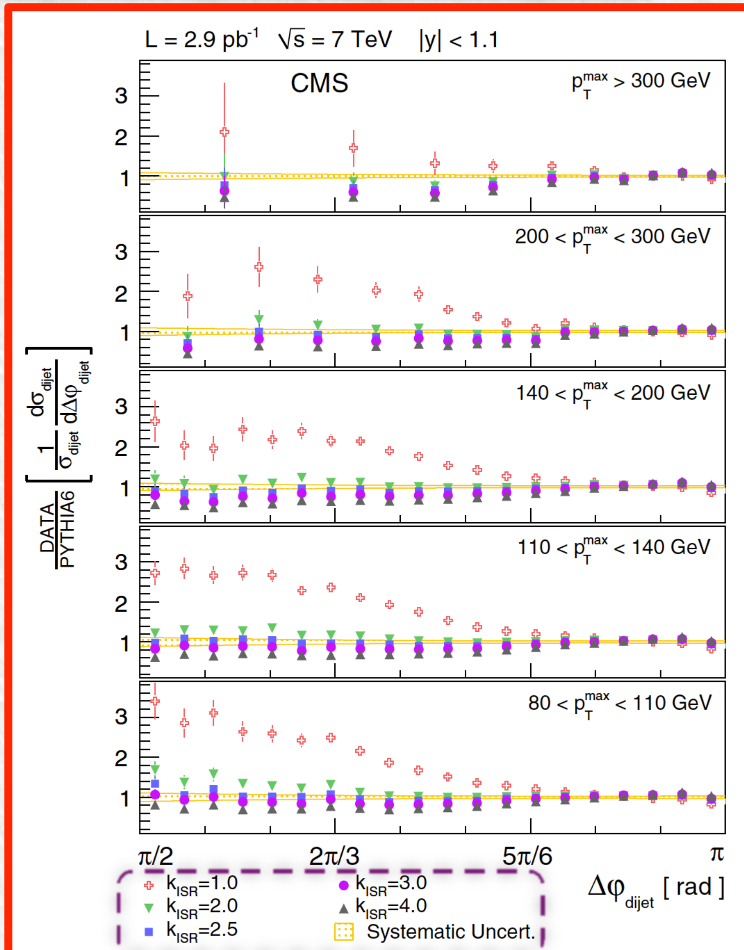
CMS-Note 004 (2011)



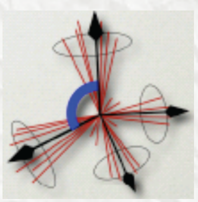
Dijet Azimuthal Distributions

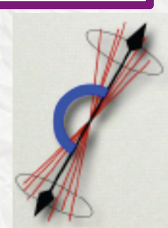


ATLAS: PRL 106,172002 (2001)



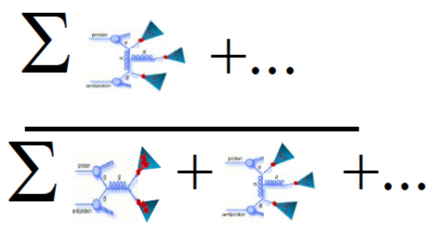
CMS: PRL 106, 122003 (2011)



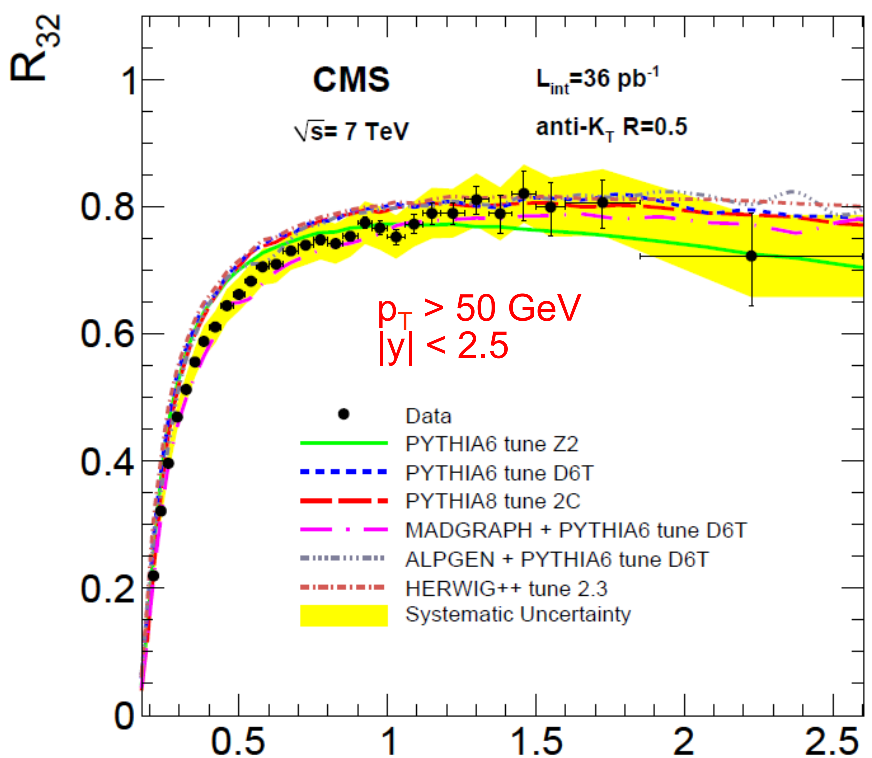


- $d\sigma_{diet}/d\Delta\phi_{dijet}$: Sensitive to Initial State Radiation Data/Theory
- Can be used to tune PYTHIA ISR (as it was done with the Tevatron data)

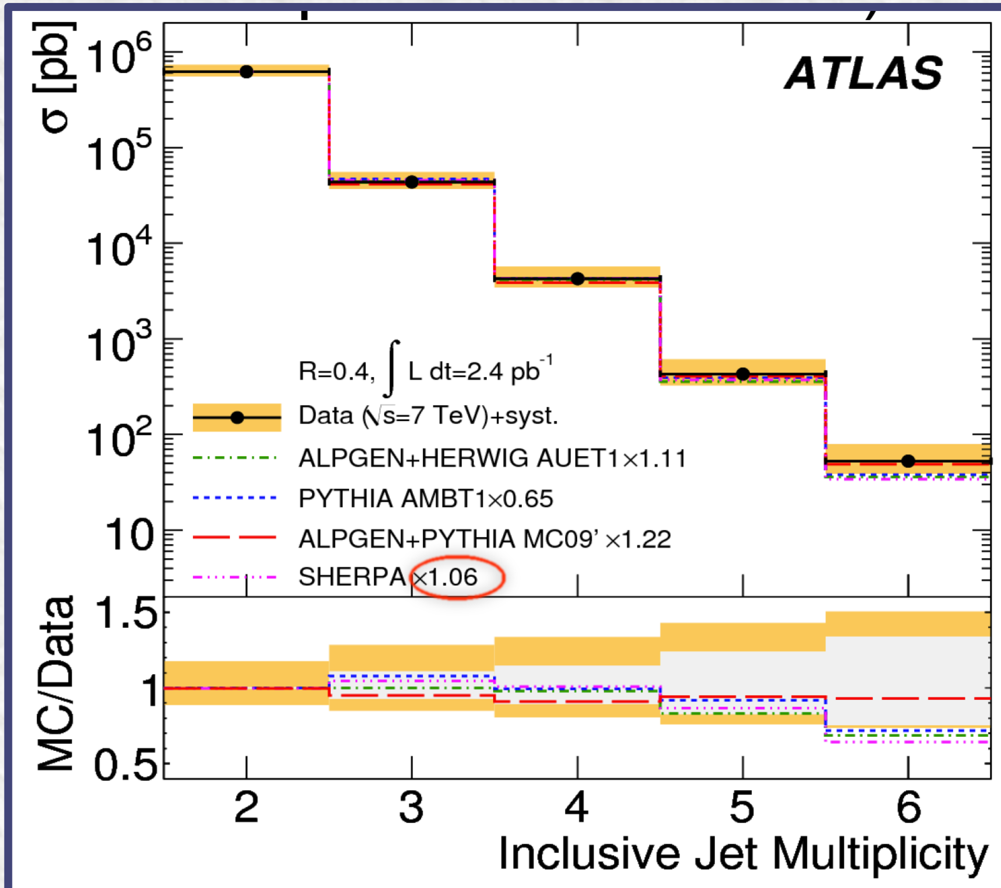
Multijet Production at LHC



$$R_{3/2} = \sigma_{3\text{-jet}} / \sigma_{2\text{-jet}} = \frac{\sum (\text{3-jet diagrams}) + \ldots}{\sum (\text{2-jet diagrams}) + (\text{2-jet diagrams}) + \ldots}$$



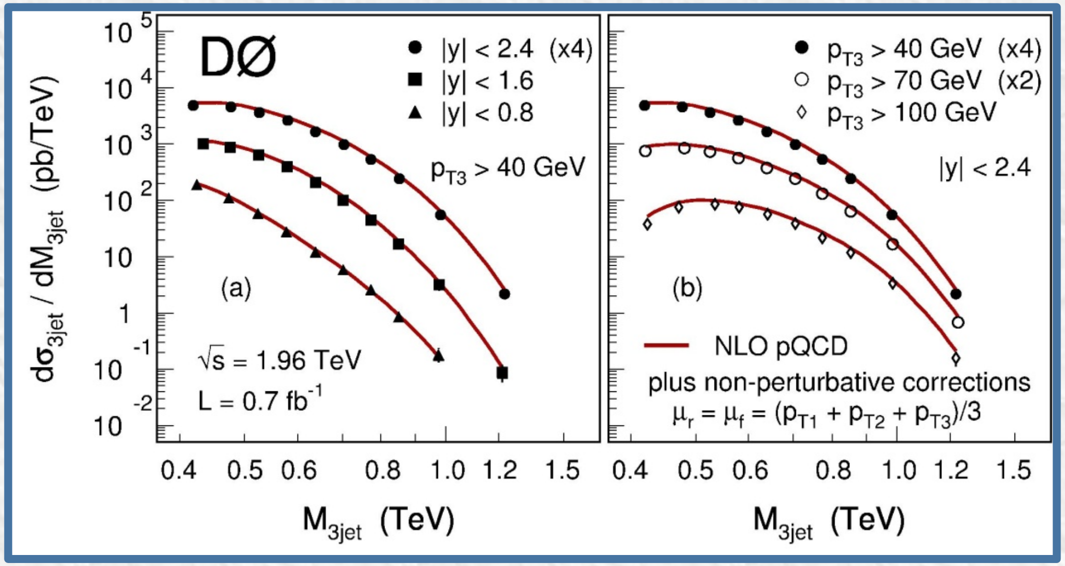
CMS: arXiv:1106.0647



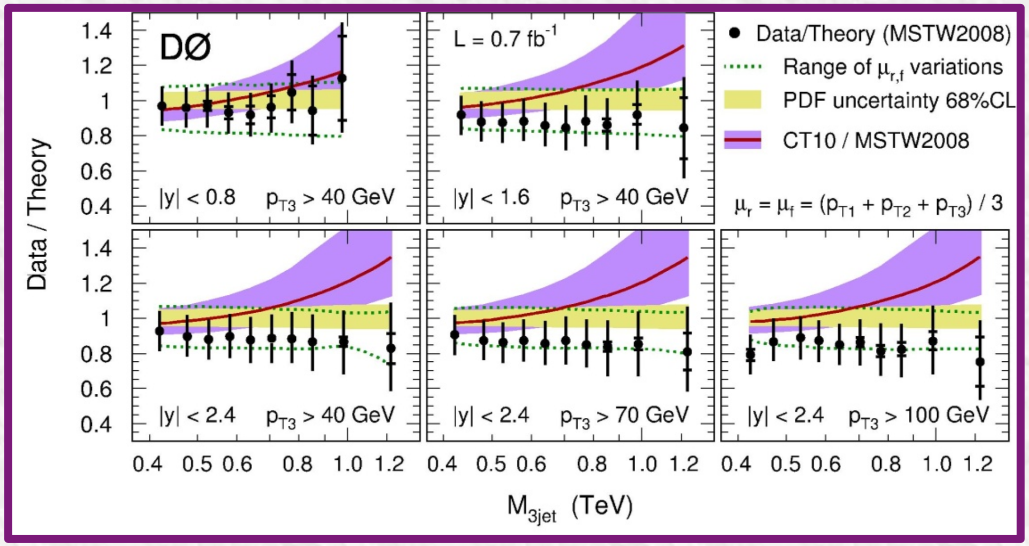
ATLAS: arXiv:1106.0647

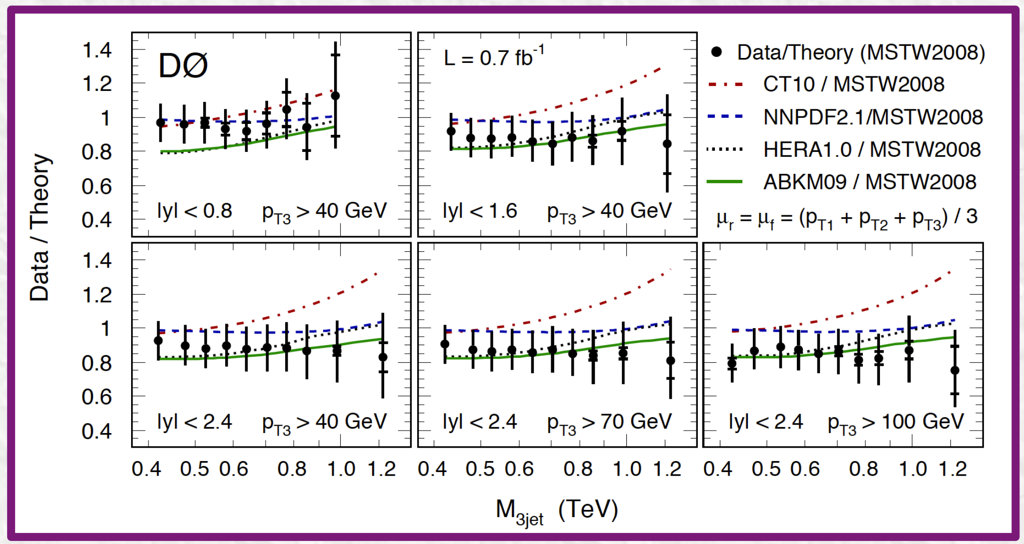
- LO multi-leg MCs agree better with the data
- SHERPA gives the best normalization

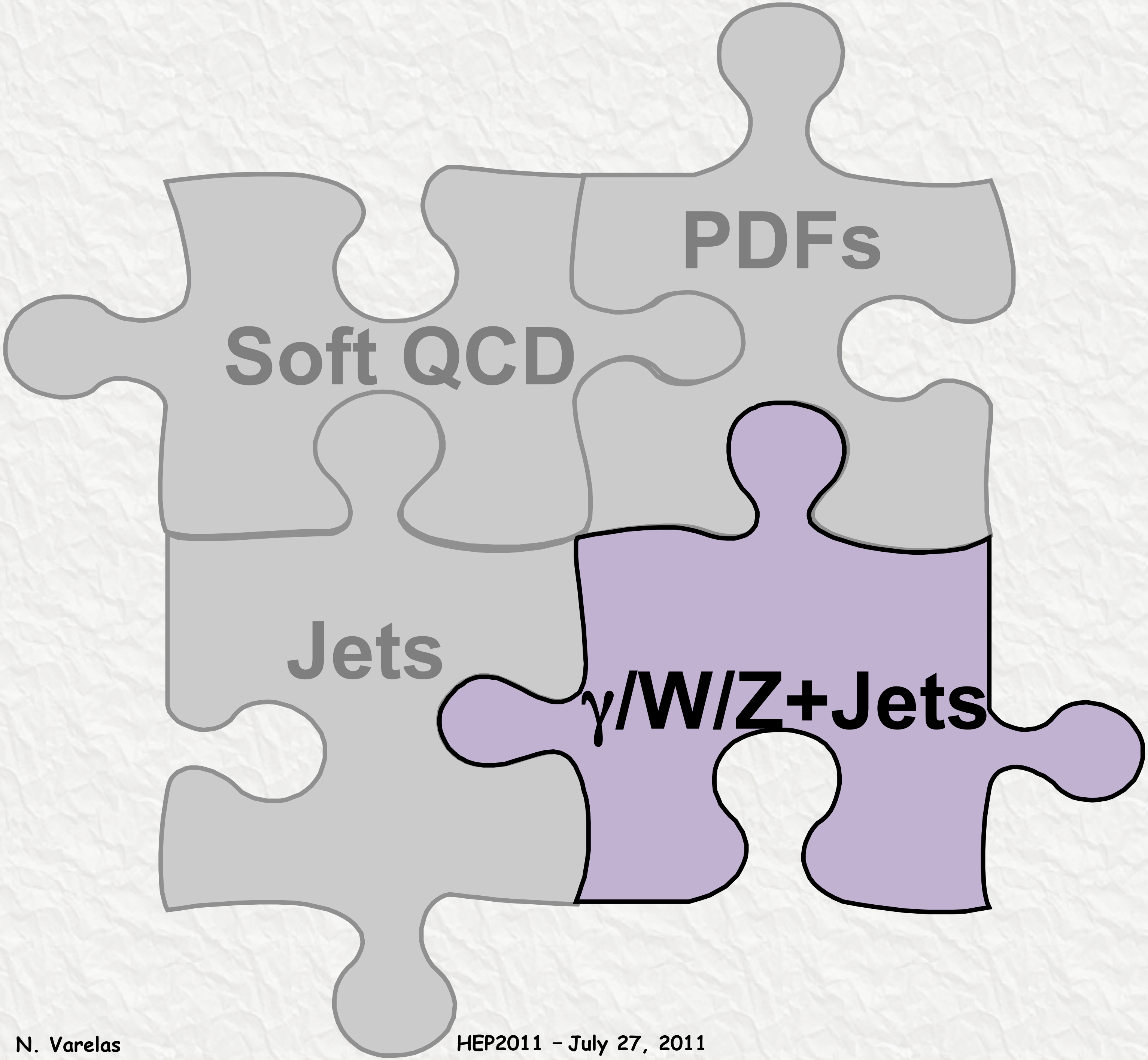
3-Jet Production at Tevatron



- **3-Jet Mass Cross Section ($d\sigma_{3jet}/dM_{3jet}$) in three rapidity bins and three p_{T3} bins**
- **Comparisons to NLO×NP with several PDF choices**

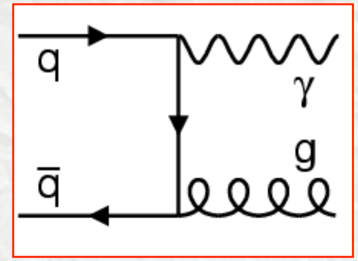


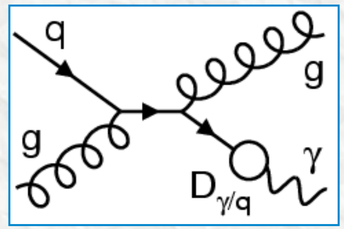


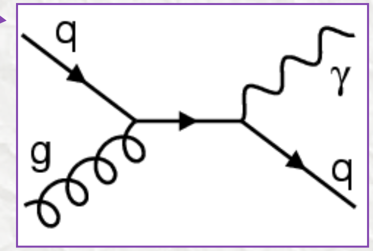

PDFs
Soft QCD
Jets
γ/W/Z+Jets

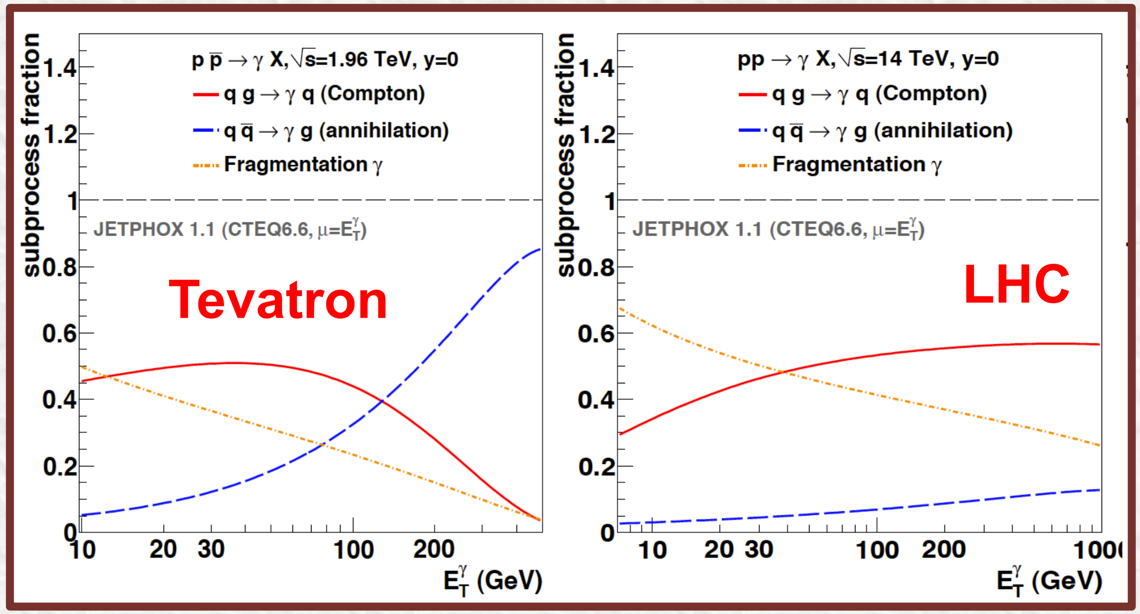
Direct Photon Production

- **Photon processes:**
  - Annihilation
  - Compton (dominate at LHC)
- **Also fragmentation contributes**
  - But suppressed with isolation
- **Directly sensitive to hard scatter**
- **Important for QCD studies, gluon PDFs, background to many discovery channels**
- **Challenging measurement**
- **Large QCD jet background**
  - Observable: isolated photons









R.Ichou & D.d'Enterria arXiv:1005.4529 (2010)

Direct Photon Production

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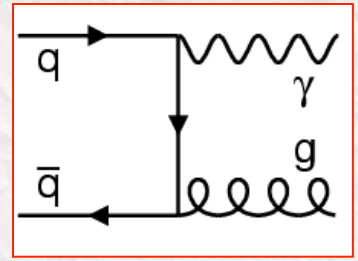

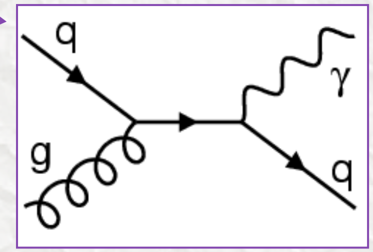

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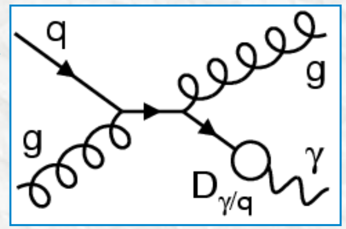

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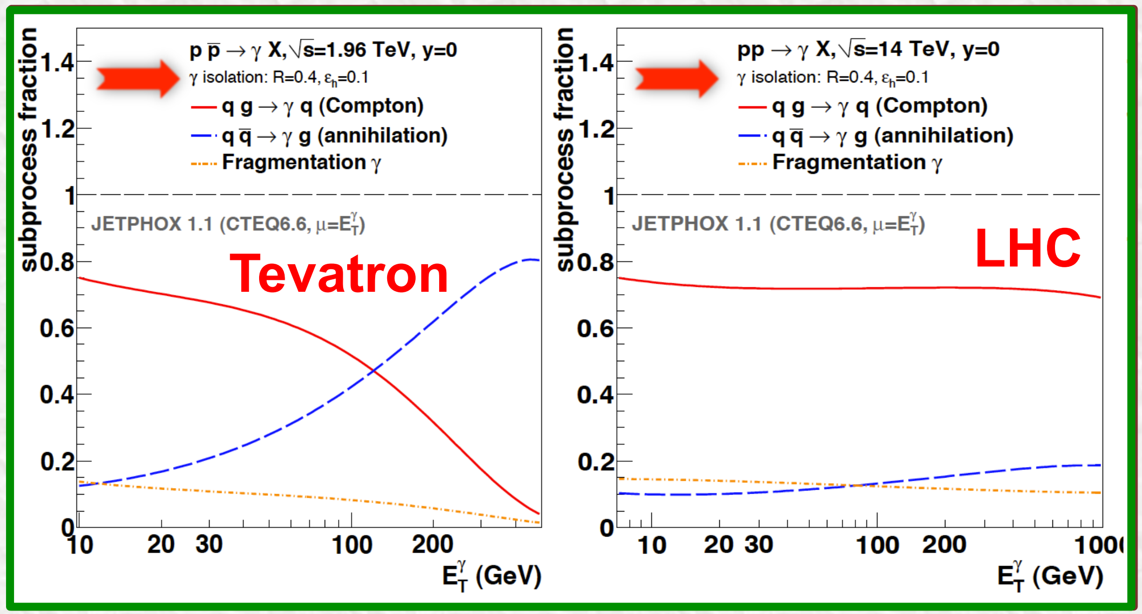
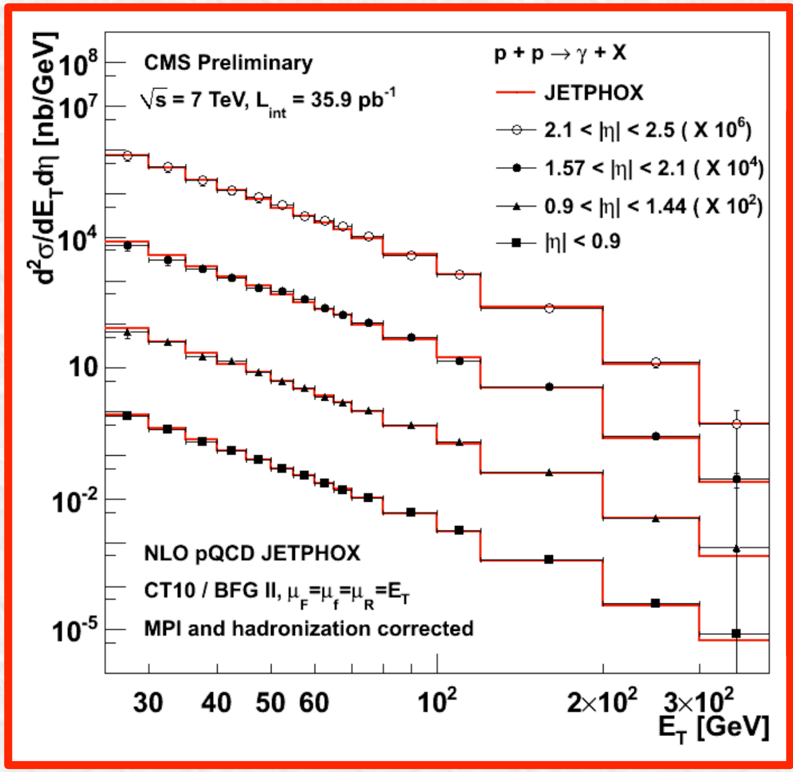
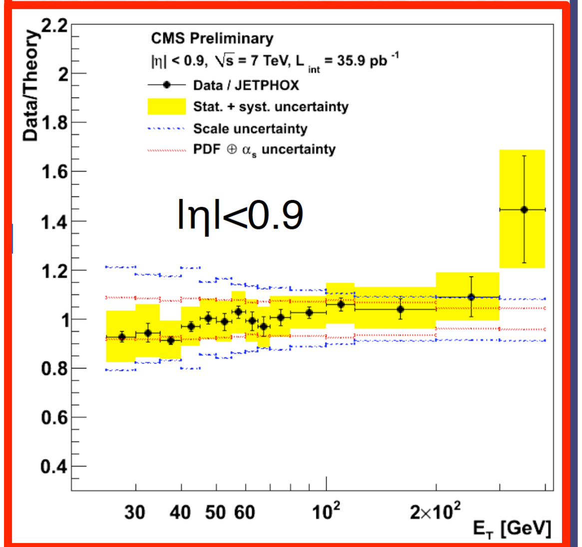
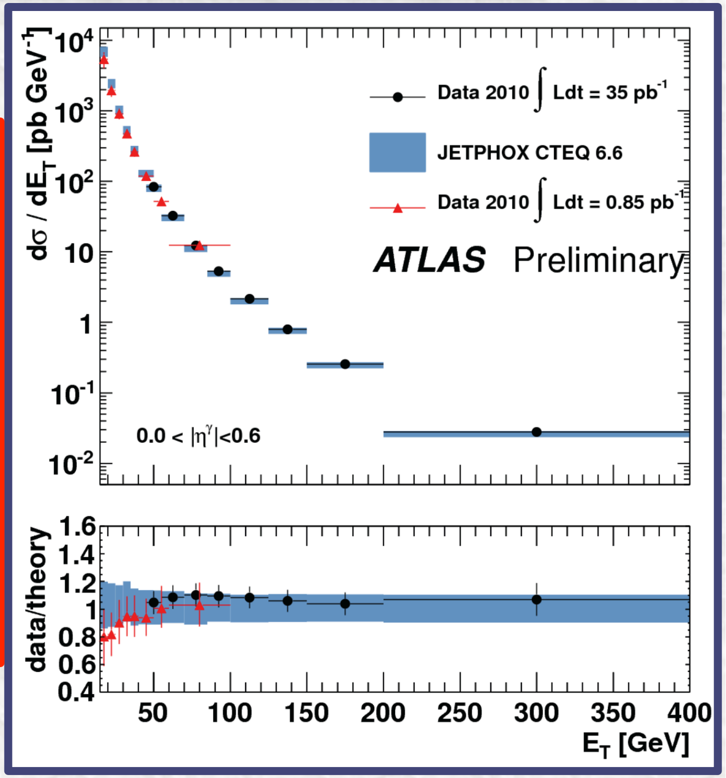


R.Ichou & D.d'Enterria arXiv:1005.4529 (2010)

Direct Photon Production at LHC







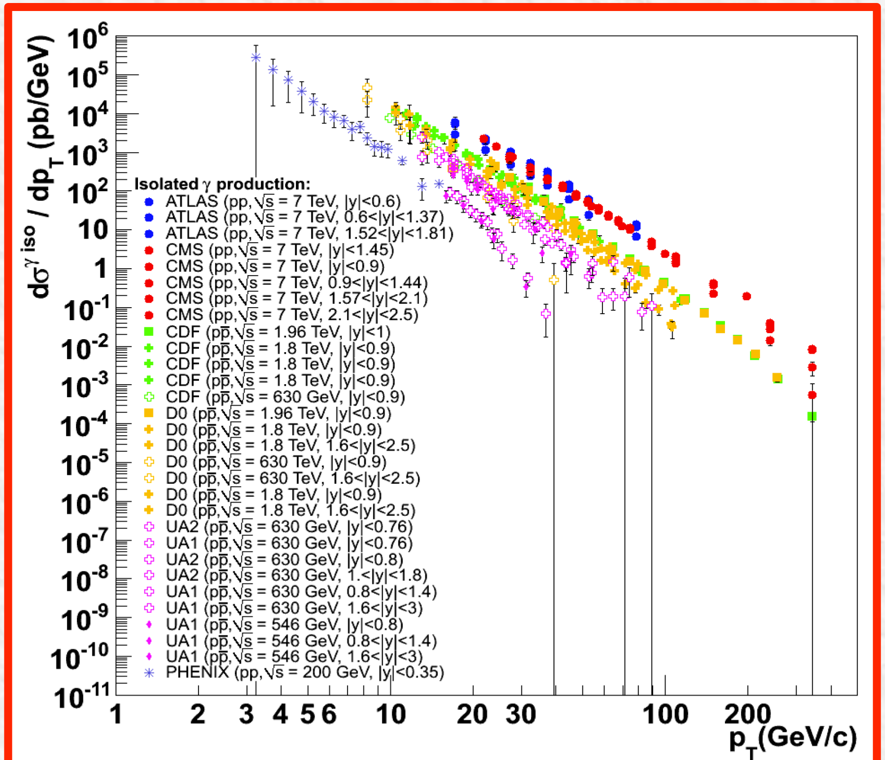
CMS: PAS-QCD-10-037

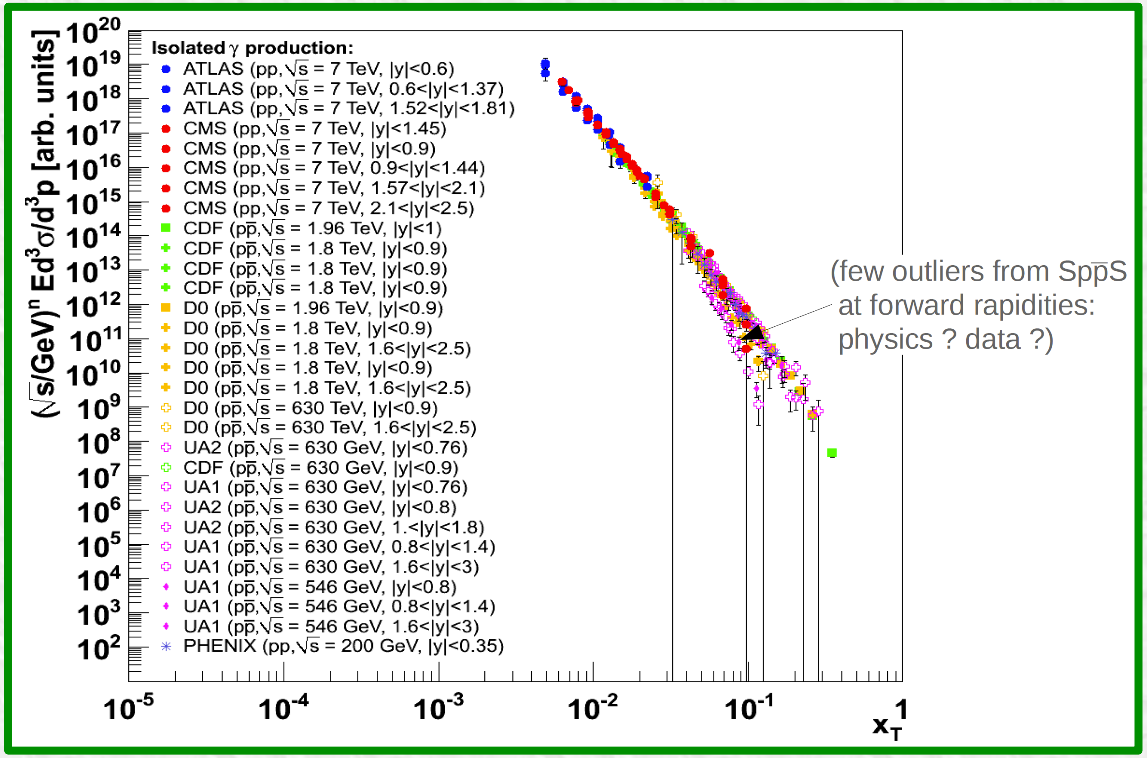
ATLAS: CONF-2011-058

- **Data/theory: Good agreement with NLO QCD**
- **Experimental uncertainties ≥ PDF uncertainty**
- **Theory scale uncertainty > PDF uncertainty**

Direct Photons and PDFs

- Sensitive to gluon PDFs via Compton sub-process
  - But it has been excluded from global fits due to theoretical difficulties to reproduce some of the data
- 350+ data points from LHC/Tevatron/SppS/RHIC covering x_T: 10^{-3}-0.4

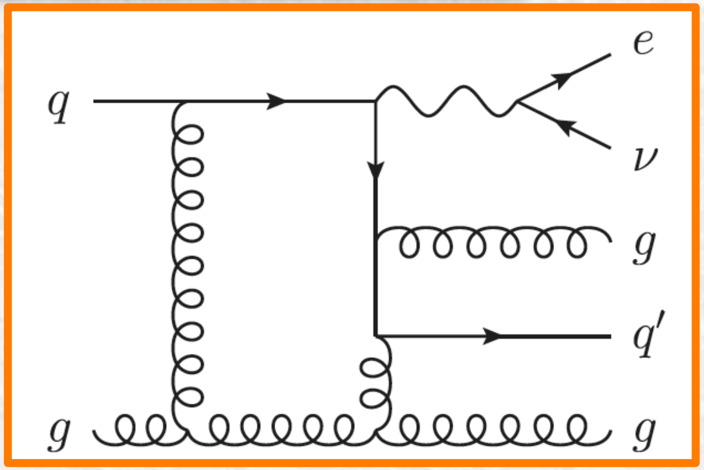


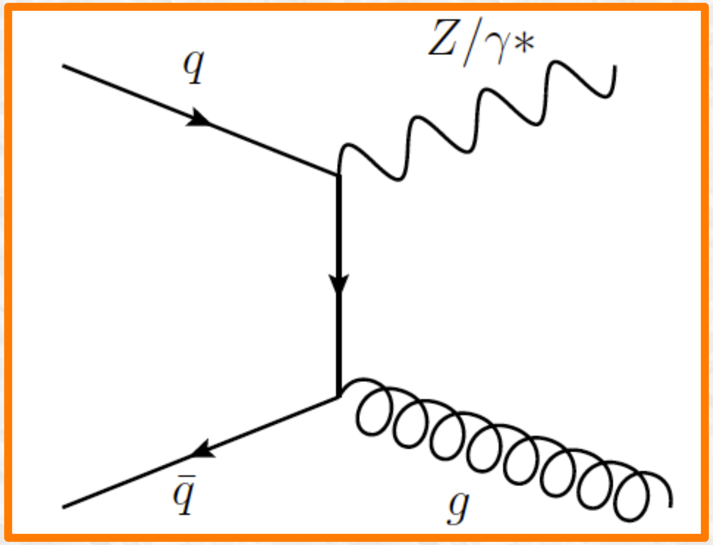


D.d'Enterria: HEP2011

W/Z+Jets Production

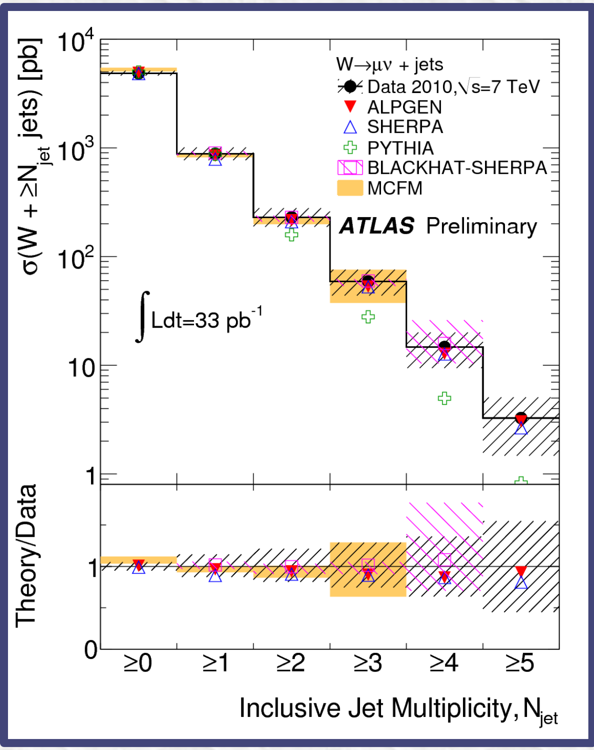
- Confronts pQCD predictions
  - Current state of the art calculations:
    - W+4 jets @ NLO (for LHC): PRL 106, 092001 (2011)
    - Z+3 jets @ NLO: PRD 82, 074002 (2010)
  - Offers a test of tree-level ME+PS event generators
    - MadGraph, ALPGEN, SHERPA
- Background to single-top and $t\bar{t}$ production, and searches for the Higgs boson and signatures beyond the SM



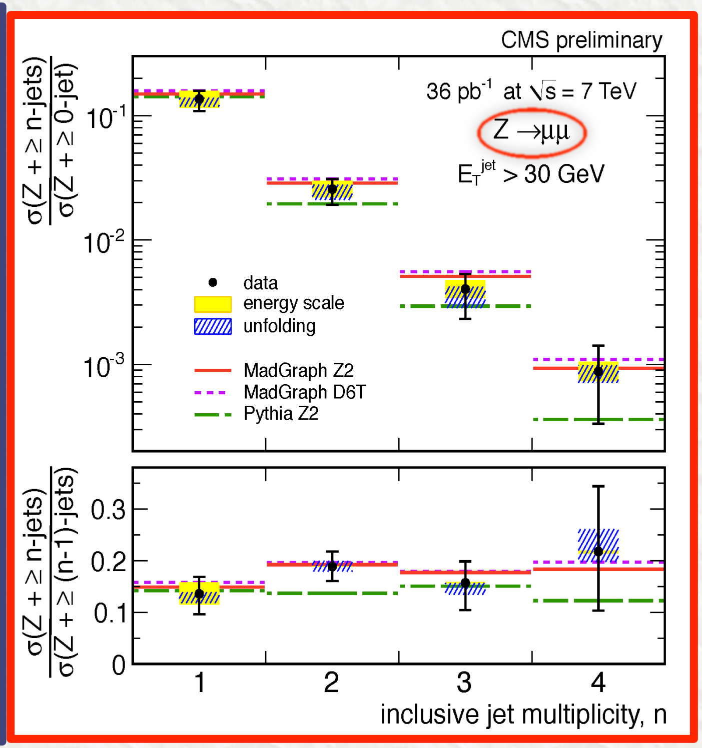


W/Z + Jets at LHC

Jet multiplicity

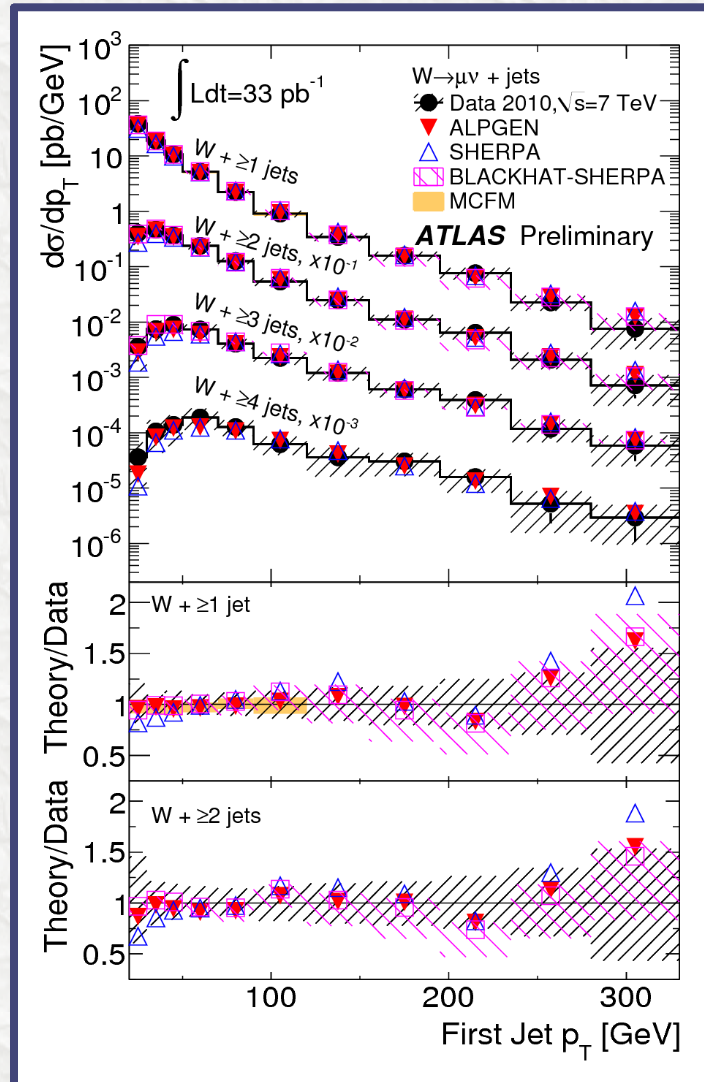


ATLAS: CONF-2011-060



CMS: PAS-EWK-10-012

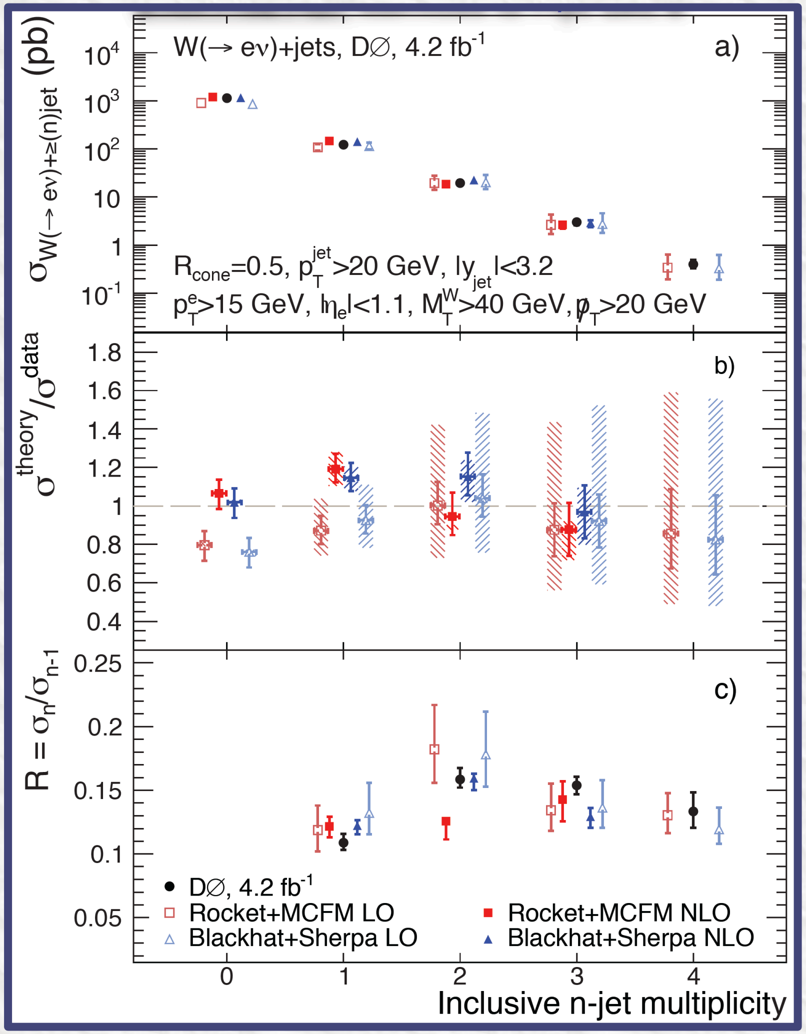
Leading jet p_T



- **Good agreement with MadGraph/ALPGEN and NLO MCFM and BLACKHAT+SHERPA**
- **Poor agreement with PYTHIA**

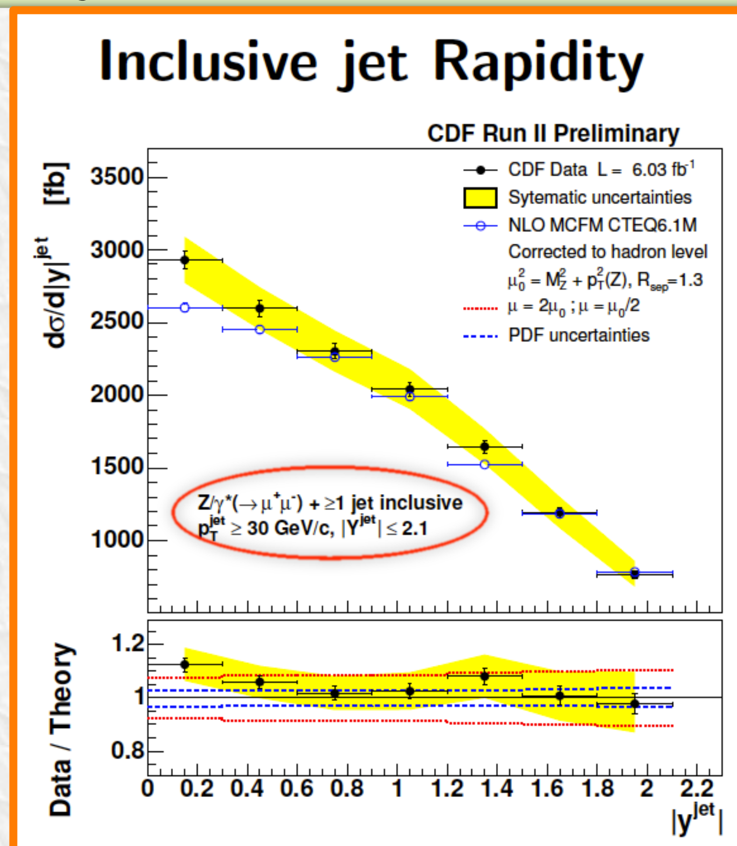
W/Z + Jets at Tevatron

Jet multiplicity



D0: arXiv:1106.1457 (2011)

- **Comparisons of jet multiplicities with NLO up to W+3 jets**
  - **Good agreement Rocket+MCFM and BLACKHAT +SHERPA**
- **Good description by MCFM of leading jet rapidity in Z+jets event**



Final Words

- QCD dynamics plays an important role at LHC physics for understanding signals and backgrounds
- Spectacular performance of the LHC and the experiments have resulted in a plethora of high quality QCD results at a record time
- The combined DIS cross section results from HERA provide better constraints of PDFs
  - Several new results confront the precision of PDFs
- More work is needed on MC tuning and on understanding the UE/MPI
- Measurements are challenging the precision of the theoretical predictions!