Determination of the Strong Coupling Constant from Inclusive Jet Production Cross Section and Double Parton Interactions in γ+3-jets events

Dmitry Bandurin
Kansas State University

on behalf of the DØ Collaboration

Fermilab Joint Experimental-Theoretical Physics Seminar
December 11, 2009

Outline

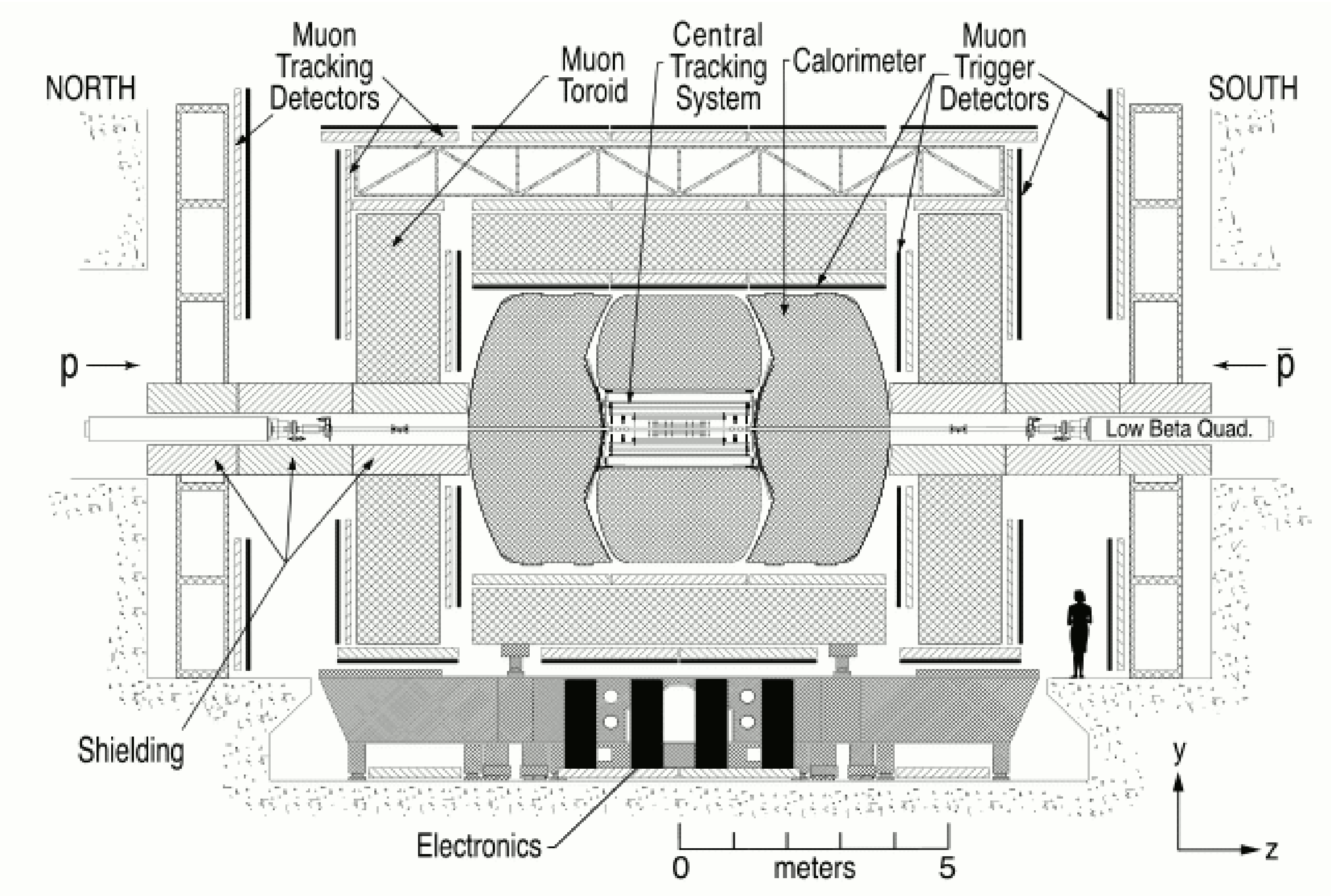
- Dzero detector

- Determination of the Strong Coupling Constant from Inclusive Jet Production Cross Section.

- Double Parton Interactions in γ+3-jets events; measurements of fraction of Double Parton events and effective cross section σ_{eff}.

- Summary

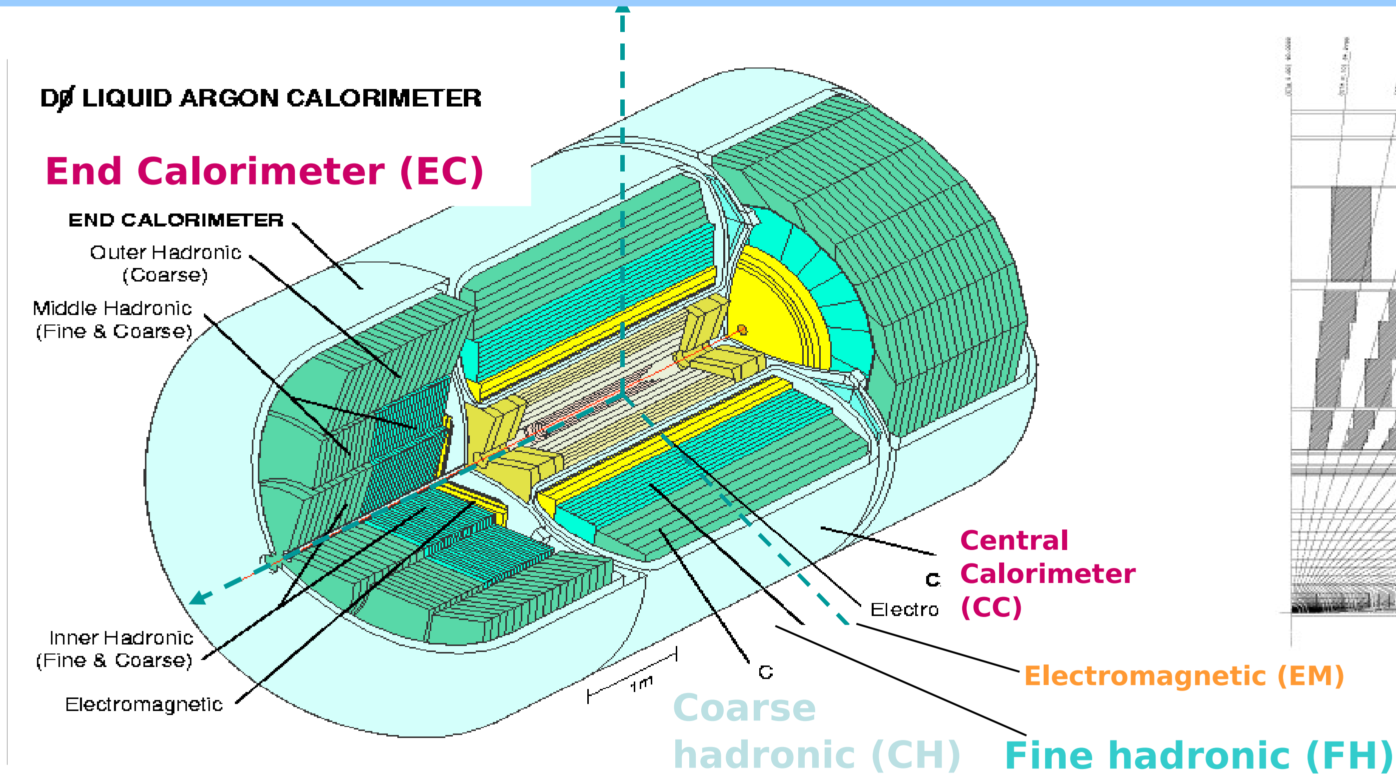
The Dzero detector

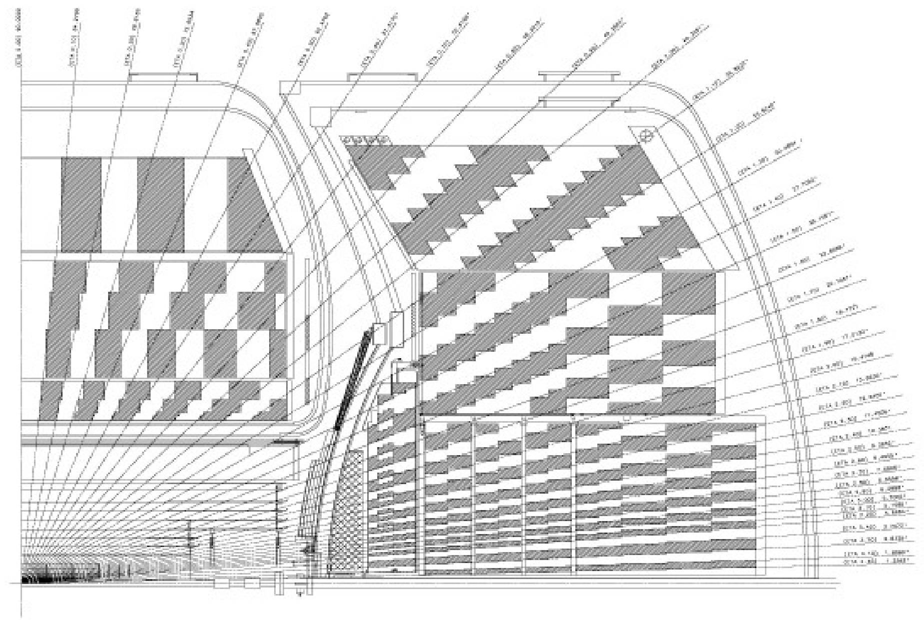


Three main systems

- Tracker (silicon and scintillating fibers)
- Calorimeter (LAr/U, some scintillators)
- Muon chambers and scintillators

Overview of the calorimeter





46000 channels

50 non-working channels

- ✓ Liquid argon active medium and (mostly) uranium absorber
- ✓ Hermetic with full coverage :$|\eta| < 4.2$
- ✓ Segmentation (towers): $\Delta\eta \times \Delta\Phi = 0.1 \times 0.1$ (0.05x0.05 in 3rd EM layer)
- ✓ Three main subregions: Central $(|\eta|<1.1)$, Intercryostat $(1.1<|\eta|<1.5)$ and End calorimeters $(1.5 < |\eta| < 4.2)$
- ✓ Stable response, good resolution

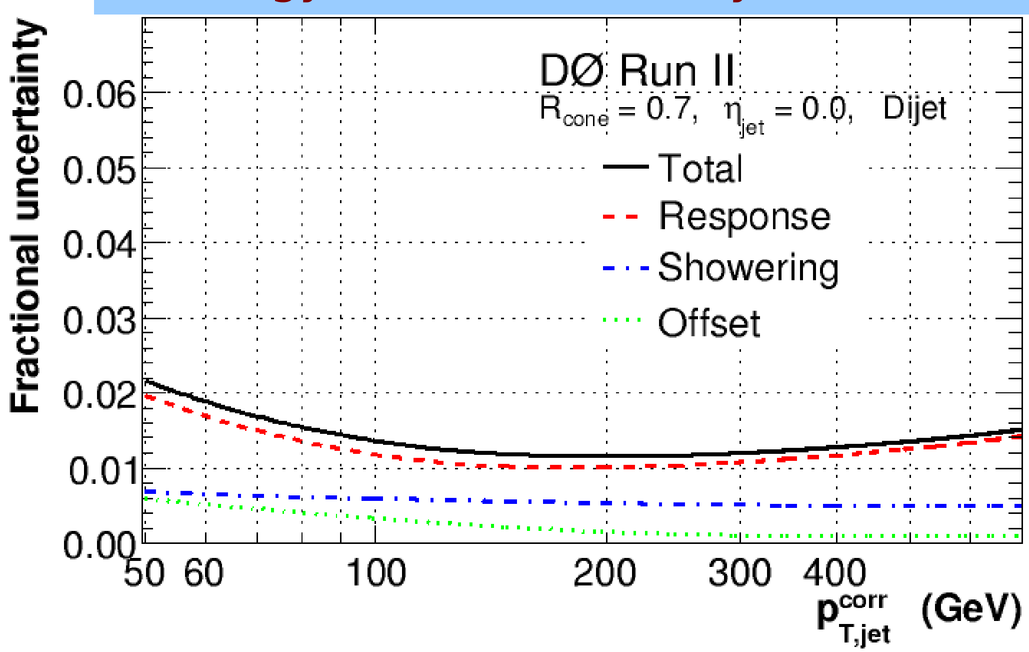
Jets, particles and partons

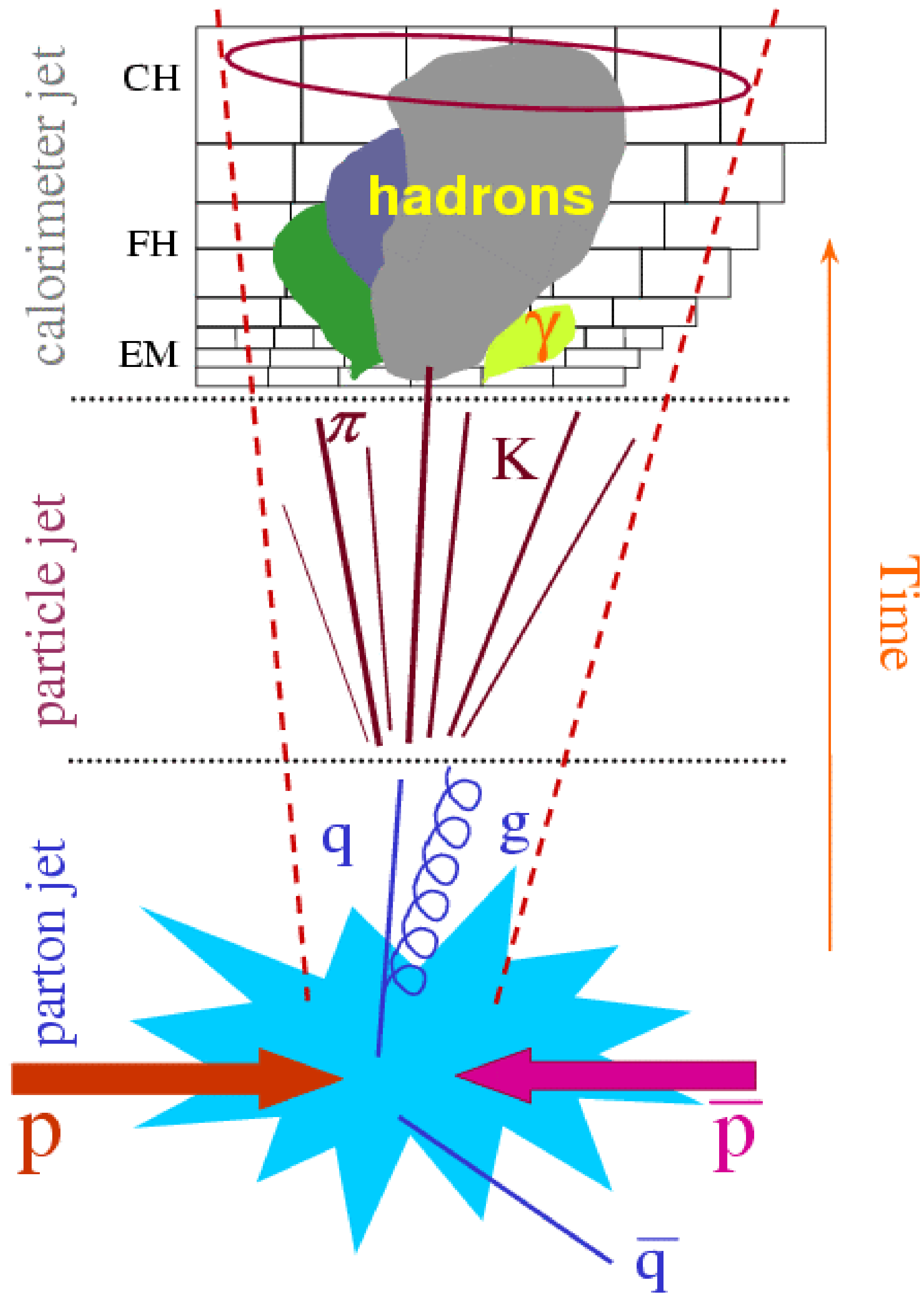
- We do not "see" partons or particles in calorimeter, only ADC counts
- ADC counts --> cell energies
- Run jet cone algorithm with
  $\Delta R = \sqrt{(\Delta y^2 + \Delta \Phi^2)} < R_{cone}$

Jet energy is corrected to the particle level using the Jet Energy Scale (JES) procedure :

- Calibrate using γ+jets, dijets and Z+jets
- JES includes: Energy Offset (energy not from the hard scattering process); Detector Response Out-of-Cone showering; Resolution

Energy scale uncertainty: 1-2% !





α_s Determination

- Motivations
- Data set
- Basic fit principle
- PDFs and α_s
- PDFs and input data
- Results

α_s and the RGE

- $\alpha_s(\mu_r)$ depends on renormalization scale μ_r
  - ✓ It is not predicted in QCD
  - ✓ It should be determined in experiment

- Renormalization Group Equation (RGE) predicts μ_r dependence

- The measured values of $\alpha_s(\mu_r)$ can be evolved to the mass of Z boson (common agreement) by using the solution to the 2-loop RGE

$$\alpha_s(M_Z) = \frac{\alpha_s(\mu_R)}{1 - \alpha_s(\mu_R)(b_0 + b_1\alpha_s(\mu_R))\ln(\mu_R/M_Z)}$$

(2- and 3-loop RGE solutions are used in this analysis)

- In jet production: μ_r = jet pT

Status of α_s measurements

From: 2008 Review of Particle Physics

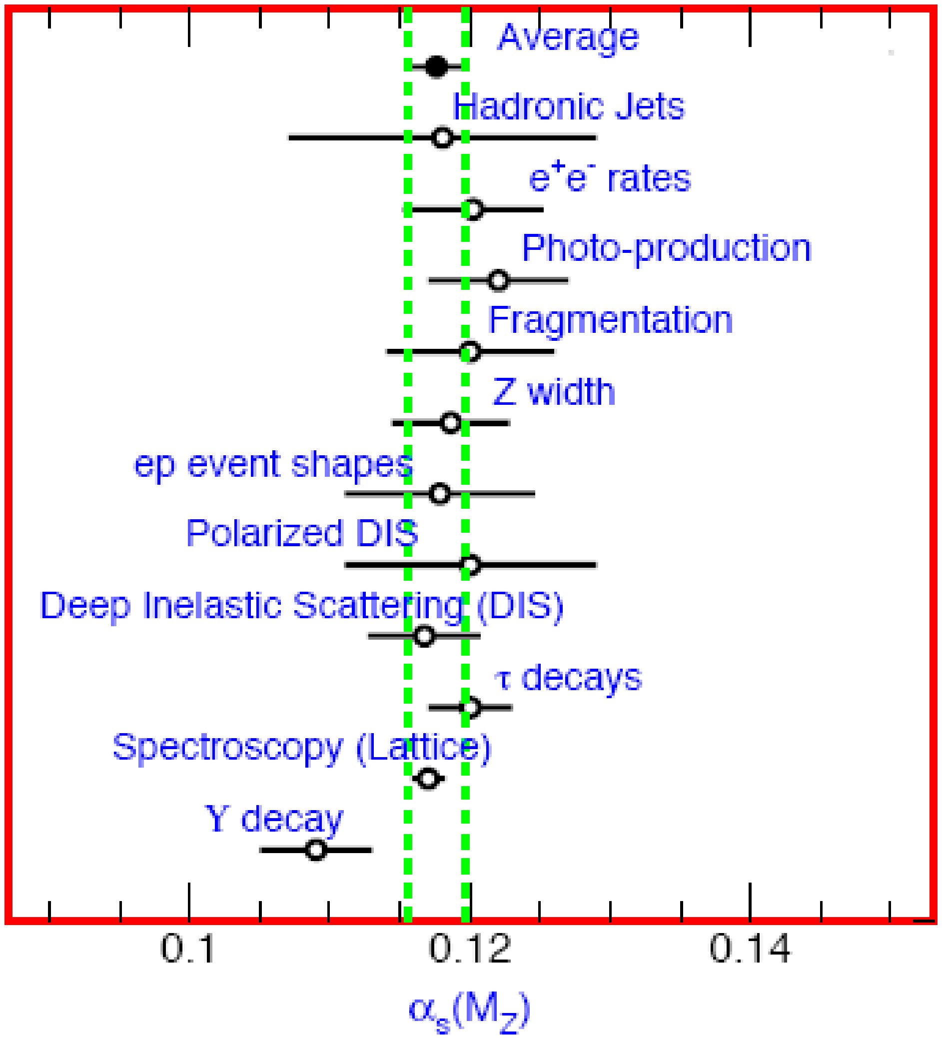


Figure 9.1: Summary of the value of $\alpha_s(M_Z)$ from various processes. The values shown indicate the process and the measured value of α_s extrapolated to $\mu = M_Z$. The error shown is the *total* error including theoretical uncertainties. The average quoted in this report which comes from these measurements is also shown. See text for discussion of errors.

Large uncertainty for entry from "Hadronic Jets"

→ Not very competitive with other relevant results

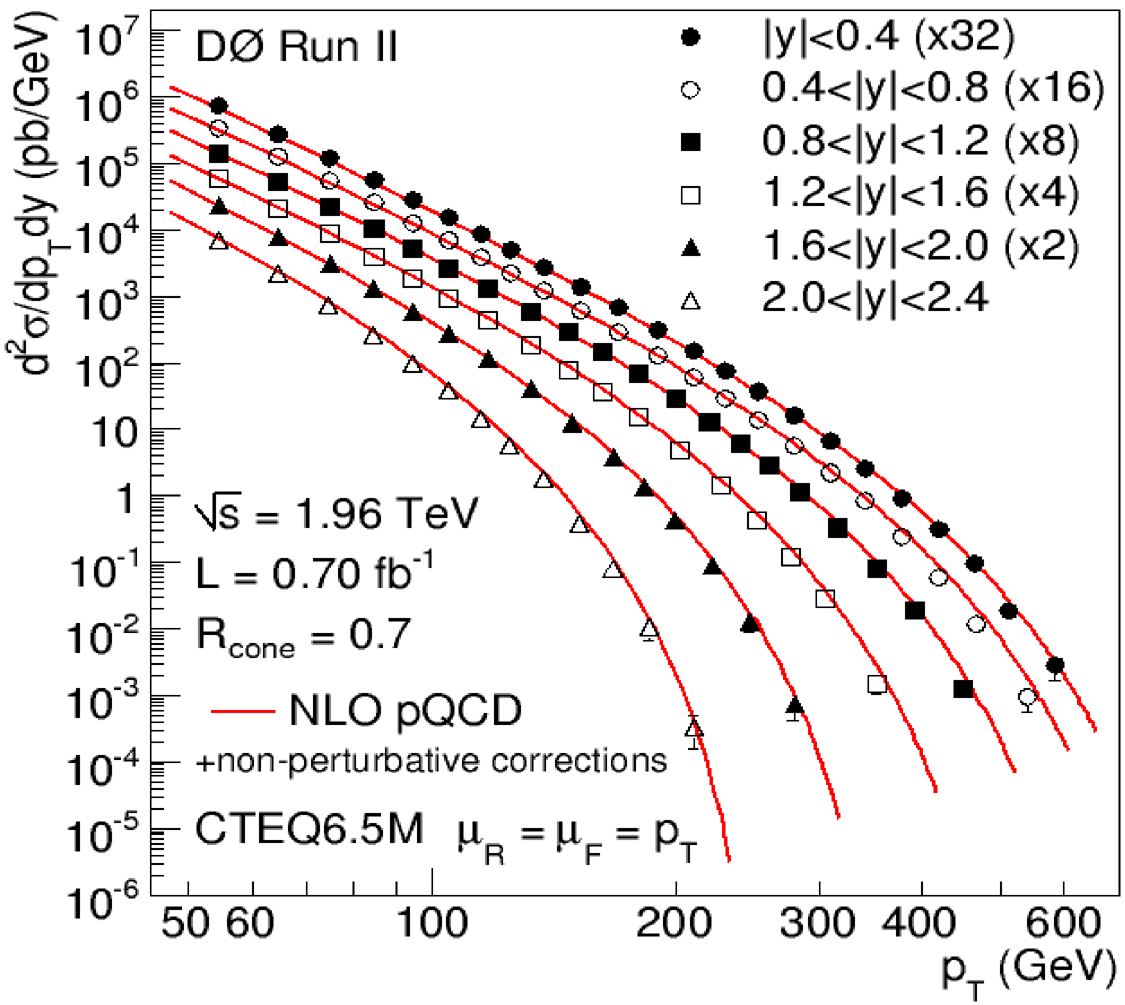
→ Can (and should) be improved!

Now we have:

- More and better data
- Better theory

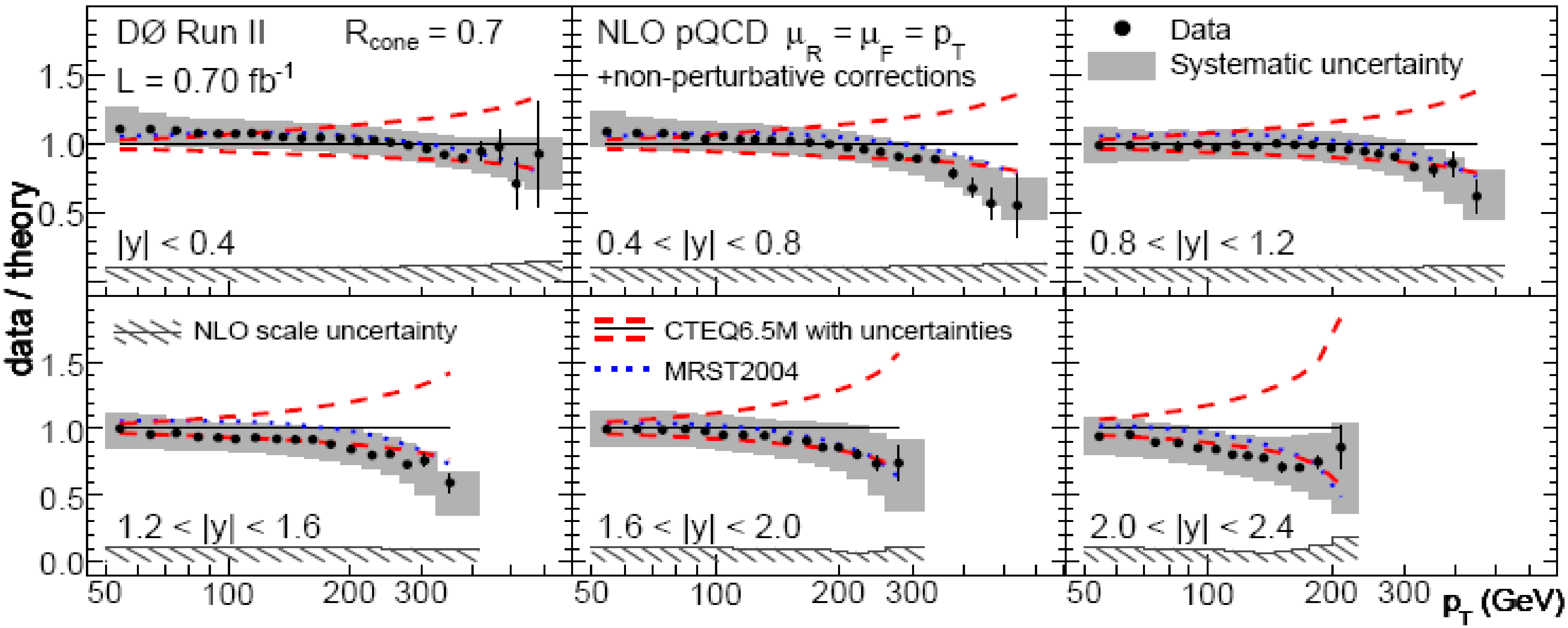
Run IIa Inclusive Jet Data (1)

D0 inclusive jet results: 110 cross section data points in six |y| regions:
PRL 101, 062001 (2008)



Run IIa Inclusive Jet Data (2)

- The systematic errors are significantly reduced due to excellent results of Jet Energy Scale group
- Overall uncertainties allow now to better distinguish a preferred PDF set



Every single data point is sensitive to $\alpha_s(pT)$

→ Sensitive to running of $\alpha_s(pT)$

→ Combined fit (of **selected** data points): $\alpha_s(Mz)$ result

Basic priciple (naïve version)

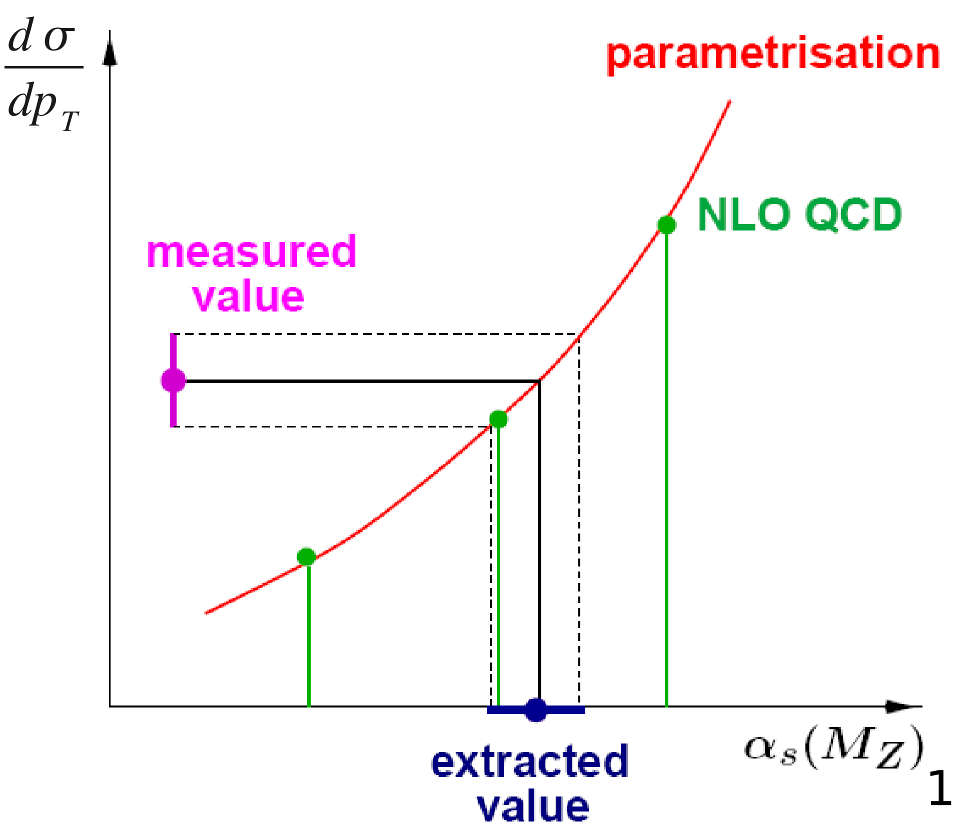
- Cross section formula:

$$\sigma_{\text{theory}}(\alpha_s) = \left(\sum_n \alpha_s^n c_n\right) \otimes f_1 \otimes f_2$$

- c_n: perturbative coefficients (→ pQCD matrix elements)
- f_1, f_2: PDFs of colliding $p, \bar{p}$

Determine α_s from data:

- Vary α_s until σ_{theory} agrees with σ_{exper}
- ...for each single bin →



α_s dependence of PDFs

- PDFs are always determined for a given value of $\alpha_s(M_Z)$

  → PDF fit results depend on α_s

Naïve x-section formula must be modified to take α_s dependence of PDFs into account:

$$\sigma_{\text{theory}}(\alpha_s) = \left(\sum_n \alpha_s^n c_n \right) \otimes f_1(\alpha_s) \otimes f_2(\alpha_s)$$

Vary α_s in matrix elements **AND** in PDFs

until $\sigma_{\text{theory}}(\alpha_s) = \sigma_{\text{exper}}$

→ Ideally need continuous α_s dependence of PDFs

→ Requires: interpolation between cross section for PDFs with different $\alpha_s(M_Z)$ values

α_s dependence of PDFs (2)

Interpolation must cover whole range of possible uncertainties
→ test interpolation over: $0.105 < \alpha_s(M_Z) < 0.130$

- MSTW2008 has **21** PDFs sets (NLO and NNLO!)
  for α_s within 0.107-0.127 in 0.001 steps (→ 21 “nodes”)
  → use interpolation for points in between those 21
  → **used for the default results**

- CTEQ6.6 has **five** PDFs sets (NLO only)
  for $\alpha_s(M_Z)$=0.112, 0.114, 0.118, 0.122, 0.125 (5 “nodes”)
  → **used for a comparison**

PDFs and input data (1)

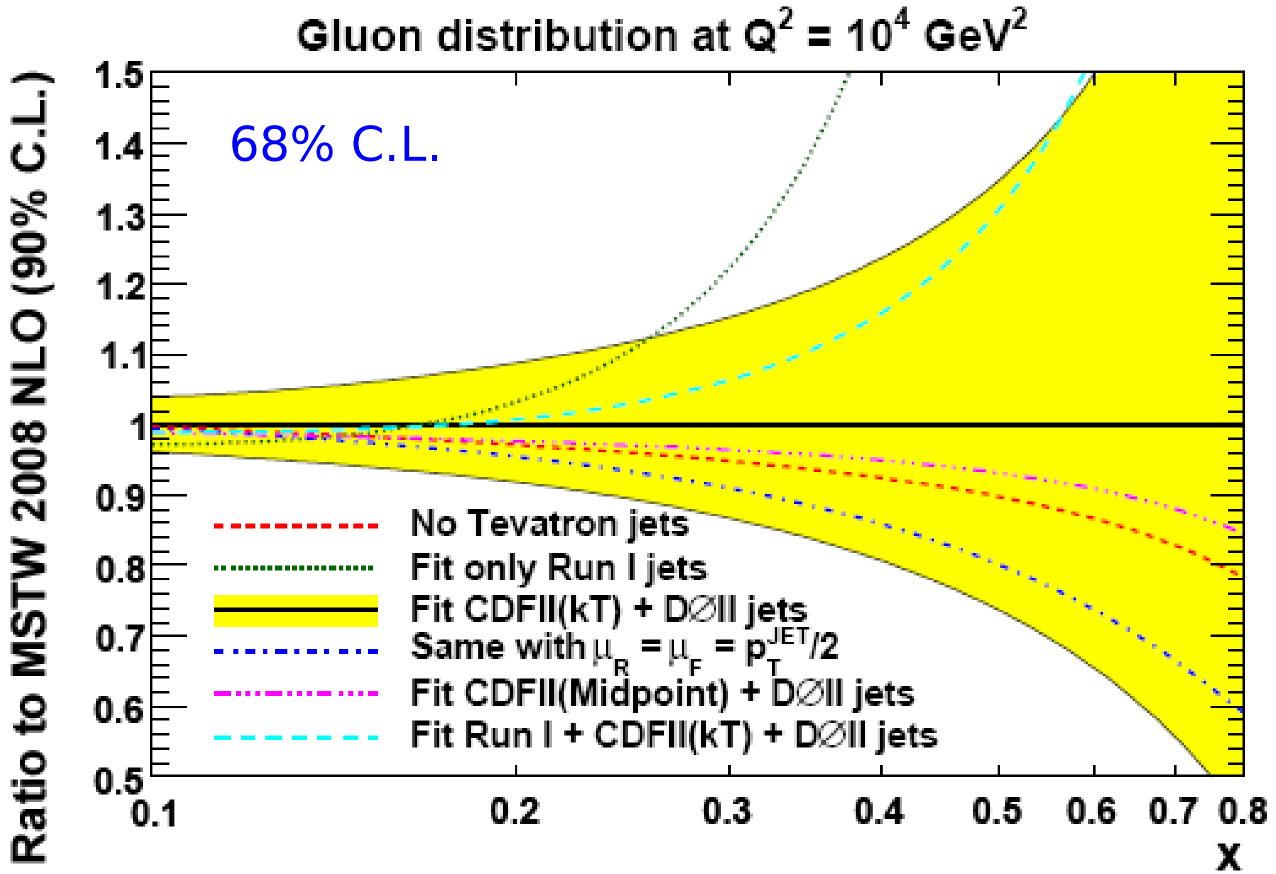
- Tevatron RunII jet data have already been used in MSTW2008 PDF fits
  → only source of high-x gluon information

- α_s extraction would be circular argument
- PDFs uncertainties are correlated to experimental uncertainties (but correlation is not documented)

→ **Restrict the data set used in the fit** to x-values where Tevatron jets are not the dominant source of information
→ Somewhere up to x = 0.2-0.3 (see next slide)

PDFs and input data (2)

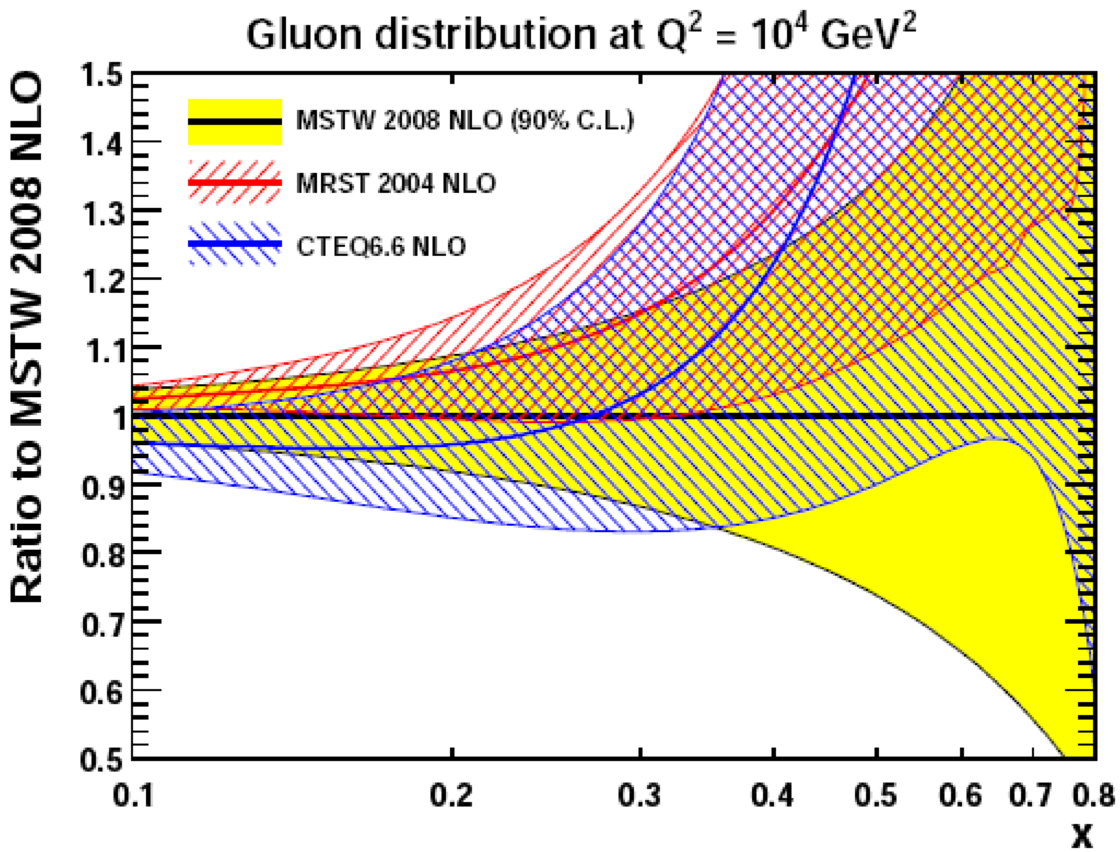
from MSTW2008 paper (arXiv:0901.0002 [hep-ph])



➔ Tevatron jet data do not affect gluon PDF for $x < 0.2 – 0.3$

PDFs and input data (3)

from MSTW2008 paper



- CTEQ6.6 does not use Tevatron Run II jet data
- But MSTW2008 and CTEQ6.6 results are in agreement for $x<0.3$

x-sensitivity?

Jet cross section has access to x-values of: (in LO kinematics)

$$x_a = x_T \frac{e^{y_1} + e^{y_2}}{2}, \quad x_b = x_T \frac{e^{-y_1} + e^{-y_2}}{2} \quad \text{with} \quad x_T = \frac{2\,p_T}{\sqrt{s}}.$$

What is the x-value for a given incl. jet data point @(pT, |y|) ?

→ Not completely constrained (unknown kinematics since we integrate over other jet)

→ Construct 'test-variable' (treat as if other jet was at y=0):

$$x_{\text{test}} = x_T \cdot (e^{|y|} + 1)/2$$

→ Apply cut on this test-variable to restrict accessible x-range

→ Requirement **x-test < 0.15** removes most of the contributions with x>0.25

→ 22 points are remaining (4 points for jet pT 50-60, ...,1 point for 130-145 GeV)

Theory

Use **two alternative** theory predictions:

pQCD:

- **NLO + 2-loop threshold corrections** ('NLO + 2-loop')
  (threshold corrections from Kidonakis/Owens)
- **NLO**

Uncertainties: scale dependence mu=pT (+ x0.5 , x2.0)

PDFs:

- MSTW2008NNLO (for 'NLO+2-loop')
- MSTW2008NLO (for NLO)

Uncertainties: from 20 PDF eigenvectors (68%CL)

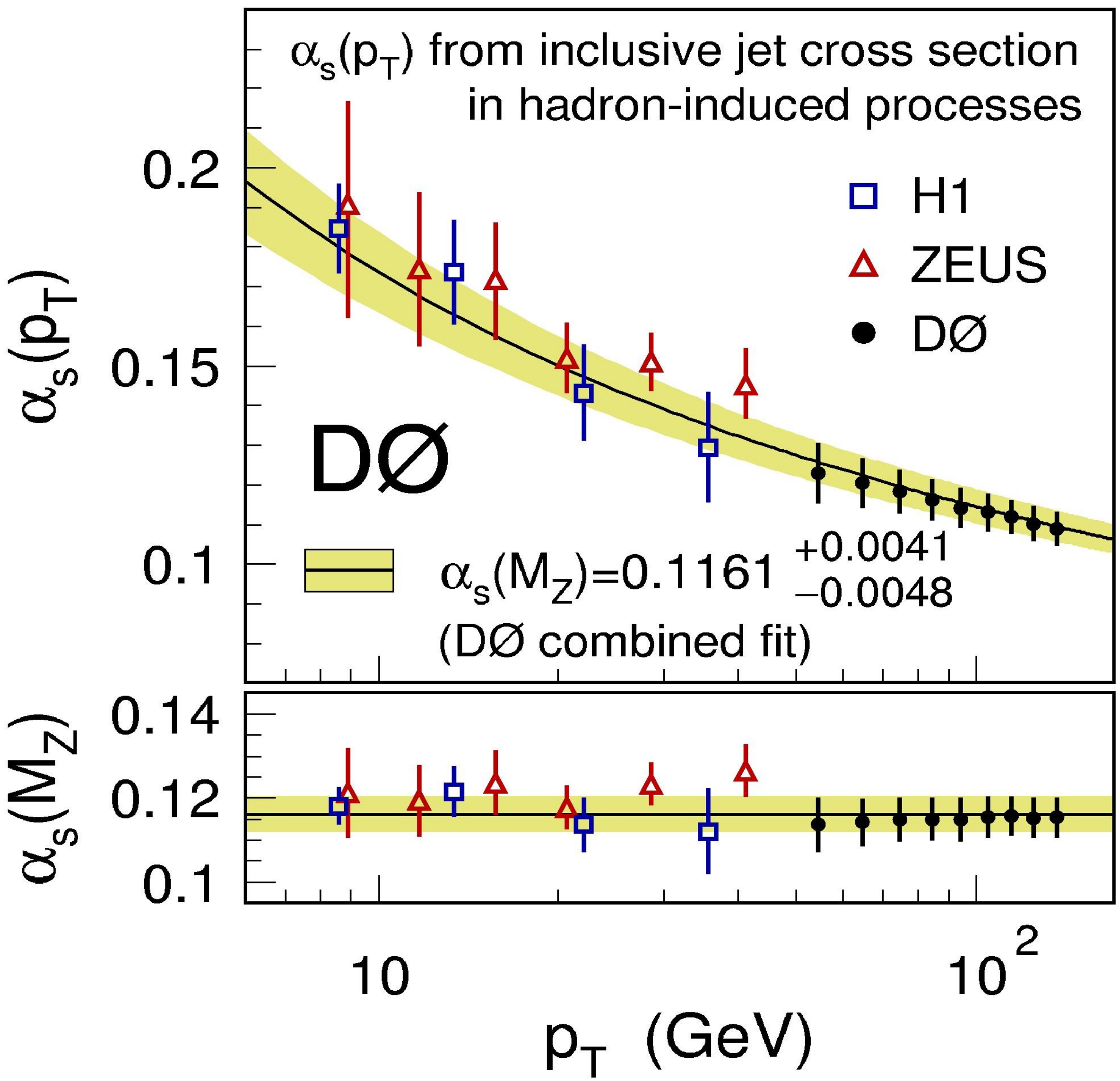
Non perturbative corrections: (hadronization / underlying events)

- from PYTHIA (as published with data)

Uncertainties: - half the size of the correction
- separately for hadronization and underlying events

Measurement of α_s(pT)

- Combine points in different |y| regions at same pT
  → Produce 9 α_s(pT) points from selected 22 data points



Theory: NLO+2-loop threshold corrections

Compare to HERA results from H1 and ZEUS
→ consistency
→ our results extend pT reach of HERA results to pT range 50-145 GeV
→ α_s is running at the highest pT measured so far!

Combined α_s(Mz)

Based on 22 inclusive jet data points with x-test<0.15

Combined α_s(Mz):

$$\alpha_s(M_Z) = 0.1161^{+0.0041}_{-0.0048}$$ NLO + 2-loop threshold corrections

$$= 0.1202^{+0.0072}_{-0.0059}$$ NLO

TABLE I: Central values and uncertainties due to different sources for the nine $\alpha_s(p_T)$ results and for the combined $\alpha_s(M_Z)$ result (bottom). All uncertainties are multiplied by a factor of 10^3.

p_T range (GeV)	No. of data points	p_T (GeV)	$\alpha_s(p_T)$	total uncertainty	experimental uncorrelated	experimental correlated	non-perturb. correction	PDF uncertainty	$\mu_{r,f}$ variation
50 - 60	4	54.5	0.1229	$^{+7.6}_{-7.7}$	±0.4	$^{+4.8}_{-4.9}$	$^{+5.8}_{-5.6}$	$^{+0.4}_{-0.6}$	$^{+1.0}_{-1.9}$
60 - 70	4	64.5	0.1204	$^{+6.2}_{-6.3}$	±0.3	$^{+4.1}_{-4.3}$	$^{+4.5}_{-4.3}$	$^{+0.6}_{-0.5}$	$^{+1.3}_{-1.5}$
70 - 80	3	74.5	0.1184	$^{+5.6}_{-5.6}$	±0.3	$^{+3.8}_{-3.9}$	$^{+4.0}_{-3.9}$	$^{+0.6}_{-0.6}$	$^{+1.0}_{-0.9}$
80 - 90	3	84.5	0.1163	$^{+5.1}_{-5.1}$	±0.3	$^{+3.6}_{-3.7}$	$^{+3.5}_{-3.5}$	$^{+0.7}_{-0.7}$	$^{+0.9}_{-0.6}$
90 - 100	2	94.5	0.1142	$^{+5.1}_{-4.9}$	±0.3	$^{+3.5}_{-3.6}$	$^{+3.5}_{-3.3}$	$^{+0.8}_{-0.8}$	$^{+1.1}_{-0.6}$
100 - 110	2	104.5	0.1131	$^{+4.7}_{-4.7}$	±0.2	$^{+3.4}_{-3.5}$	$^{+3.1}_{-3.0}$	$^{+0.8}_{-0.8}$	$^{+1.1}_{-0.6}$
110 - 120	2	114.5	0.1121	$^{+4.2}_{-4.4}$	±0.2	$^{+3.1}_{-3.3}$	$^{+2.5}_{-2.7}$	$^{+0.7}_{-0.8}$	$^{+1.2}_{-0.7}$
120 - 130	1	124.5	0.1102	$^{+4.4}_{-4.4}$	±0.2	$^{+3.2}_{-3.4}$	$^{+2.6}_{-2.6}$	$^{+0.9}_{-0.9}$	$^{+1.4}_{-0.9}$
130 - 145	1	136.5	0.1090	$^{+4.2}_{-4.3}$	±0.3	$^{+3.1}_{-3.4}$	$^{+2.3}_{-2.4}$	$^{+0.9}_{-0.9}$	$^{+1.5}_{-0.9}$
50 - 145	22	M_Z	0.1161	$^{+4.1}_{-4.8}$	±0.1	$^{+3.4}_{-3.3}$	$^{+1.0}_{-1.6}$	$^{+1.1}_{-1.2}$	$^{+2.5}_{-2.9}$

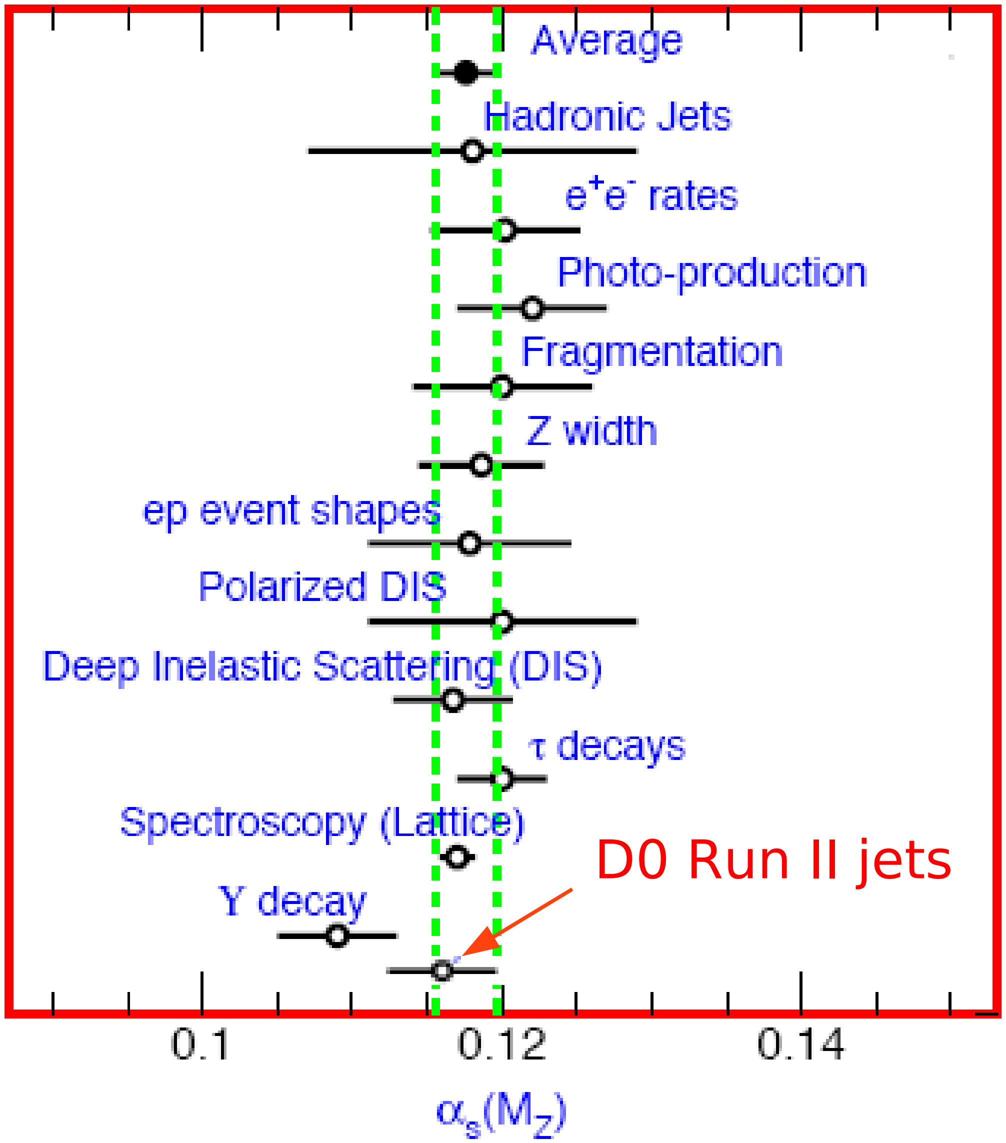
Main correlated uncertainties: JES, pT-resolution, luminosity

Summary on α_s

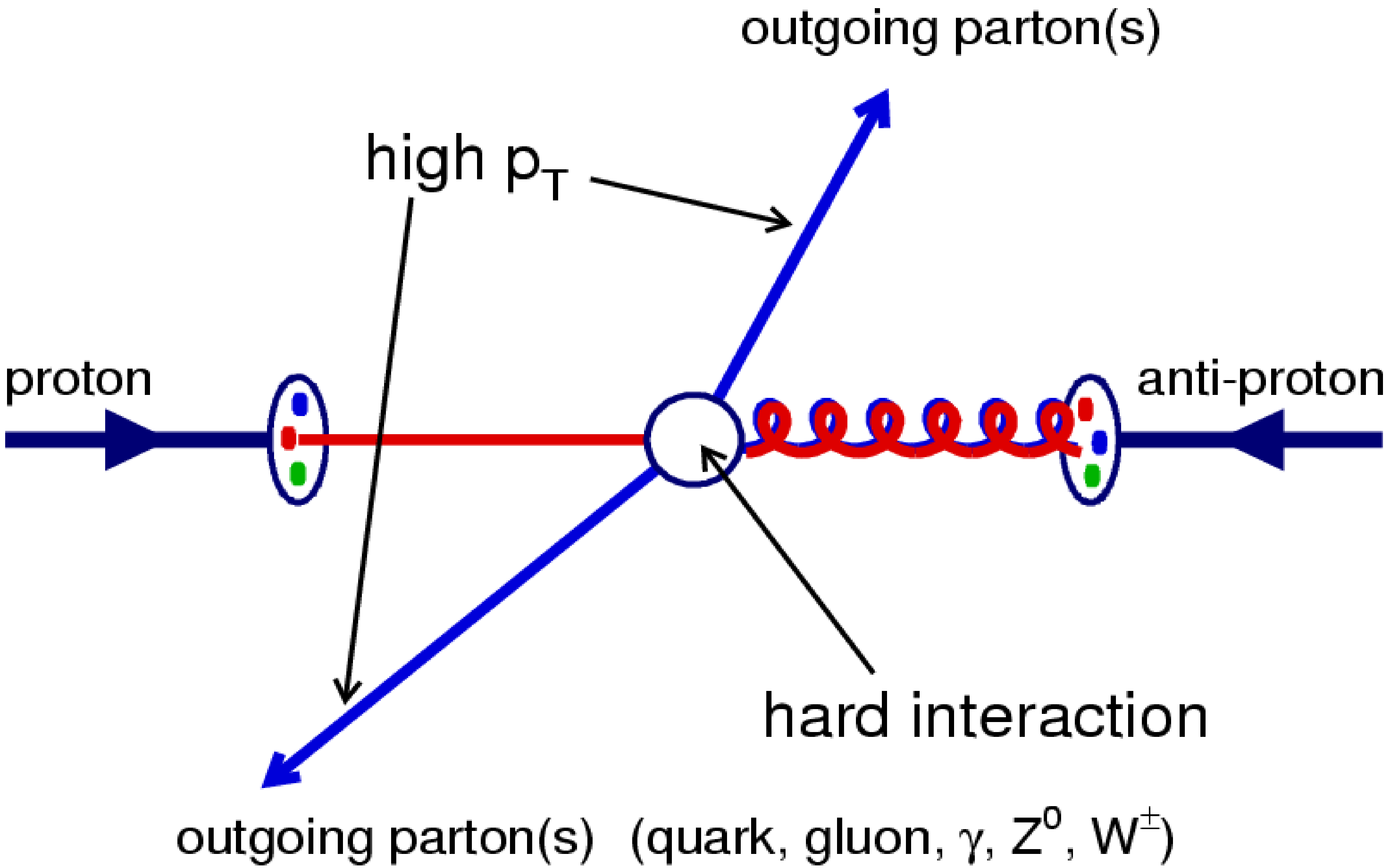
New α_s result from D0 inclusive jet pT cross sections

$$\alpha_s(M_Z) = 0.1161^{+0.0041}_{-0.0048}$$

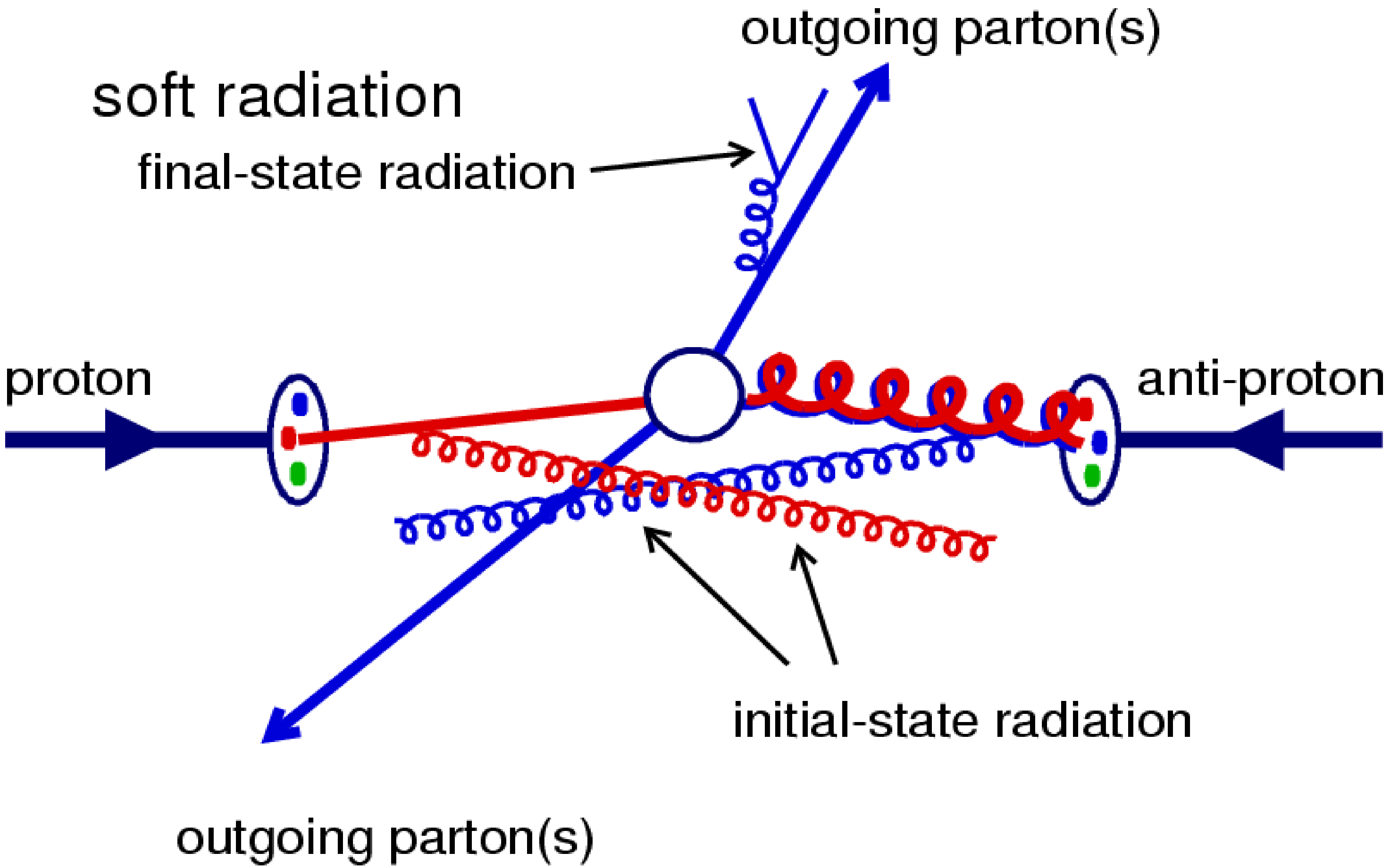
- → The only Run II result on α_s
- → Improvement by about factor 3 as compared with Run I
- → Comparable precision with HERA jets (0.1189 ±0.0032)
- → Accepted by PRD RC (arXiv.org:0911.2710 [hep-ex])



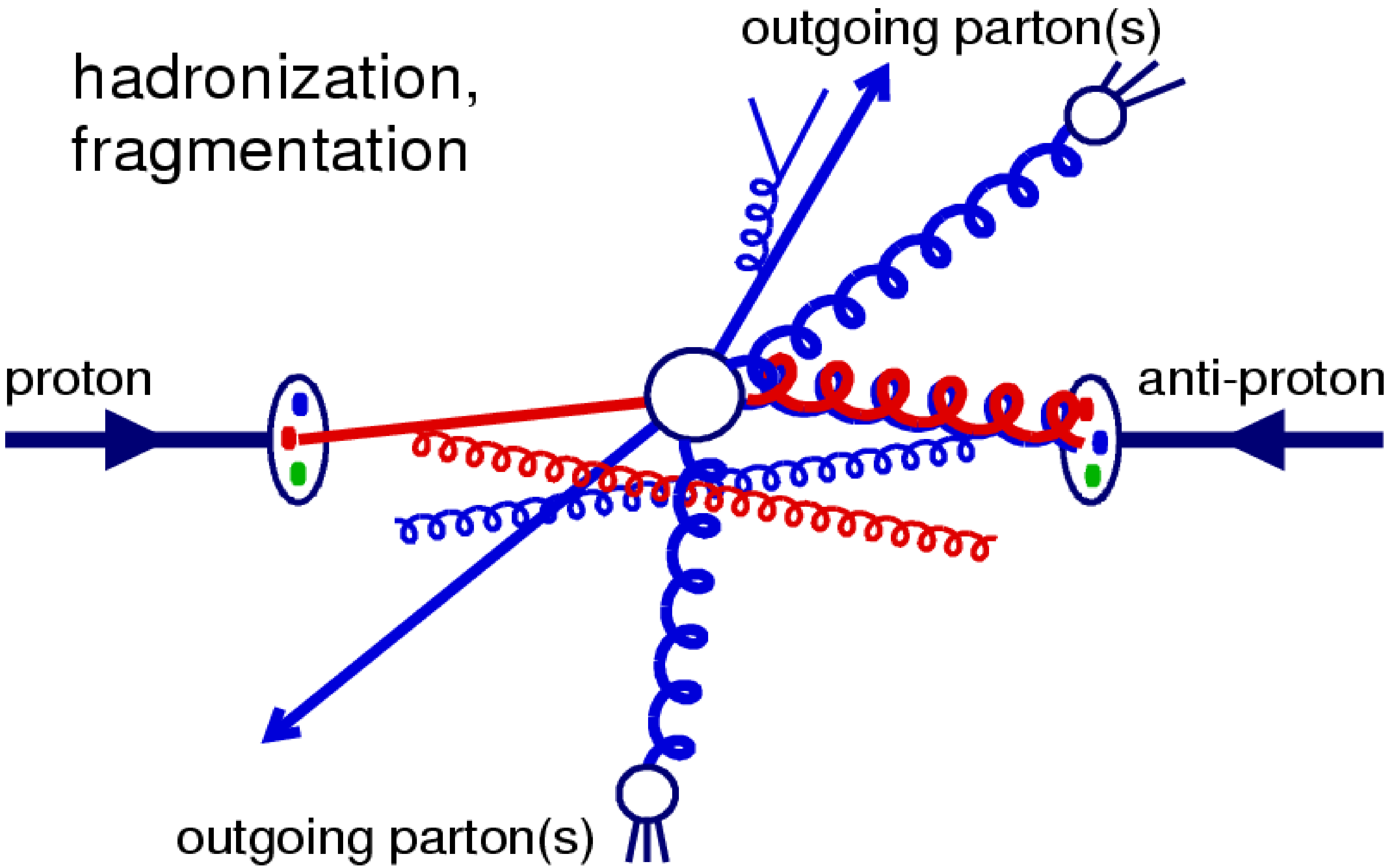
Hadron-Hadron Collision



Hadron-Hadron Collision

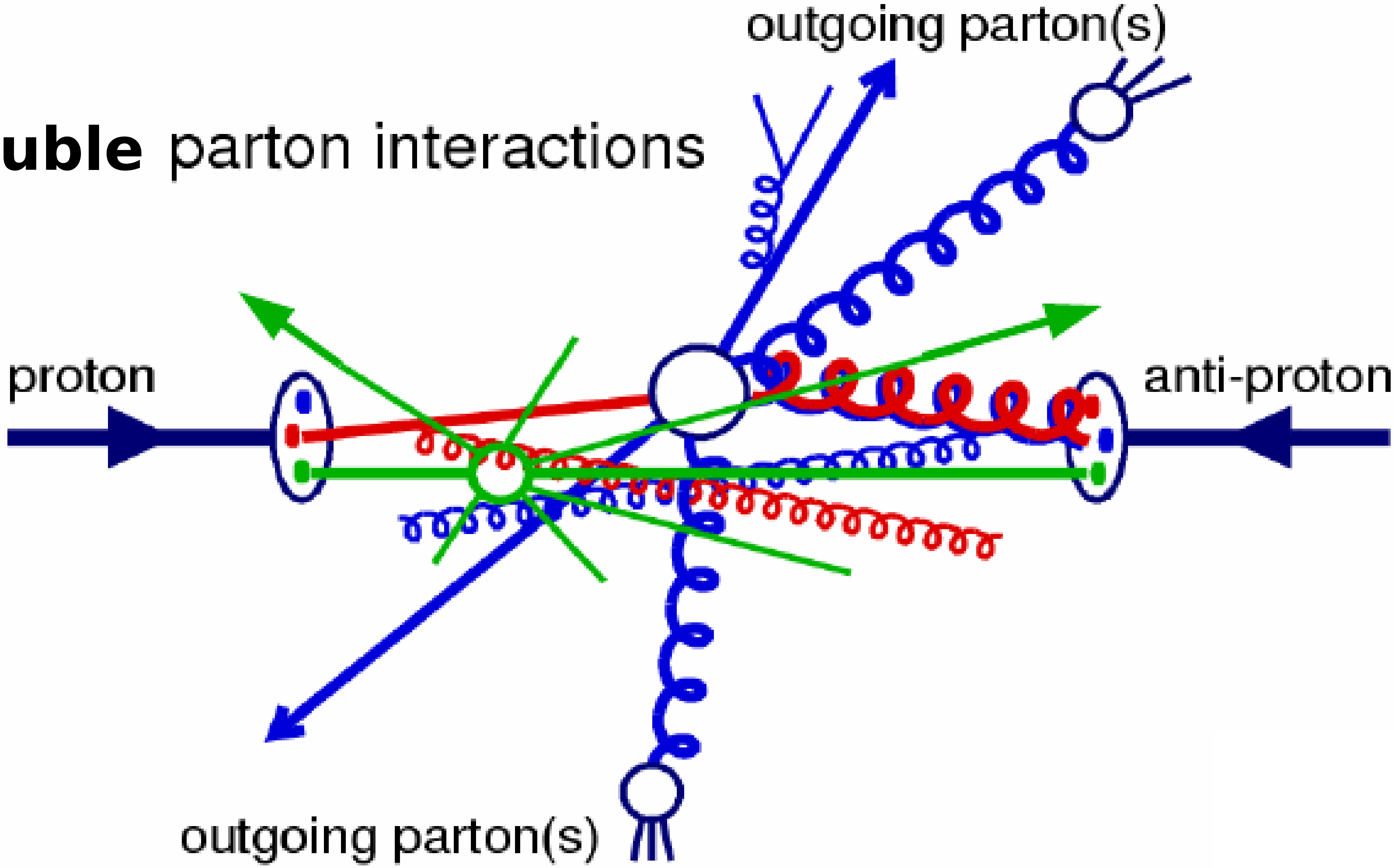


Hadron-Hadron Collision

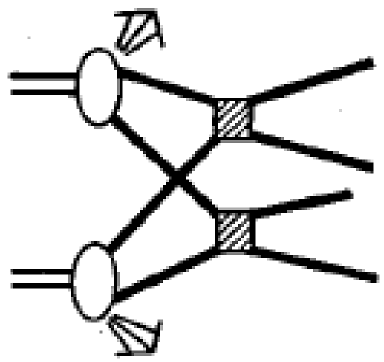


Hadron-Hadron Collision: from Single to Double parton interactions

Double parton interactions



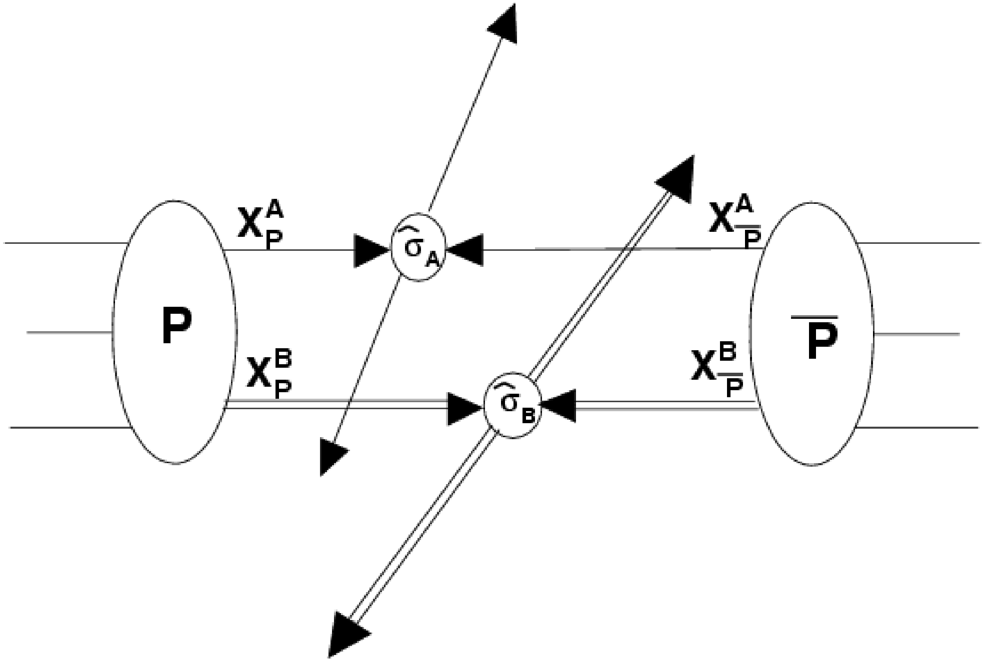
Double Parton Interactions in γ+3 jets events



- Motivations
- Event topology
- Discriminating variables
- Fraction of double parton events
- Effective cross-section measurement
- Conclusion

Double parton and effective cross sections

$$\sigma_{DP} = \frac{\sigma_A \sigma_B}{\sigma_{eff}}$$



σ_{DP} - double parton cross section for processes A and B

σ_{eff} - factor characterizing size of effective interaction region

→ contains information on the spatial distribution of partons.

Uniform: σ_{eff} is large and σ_{DP} is small

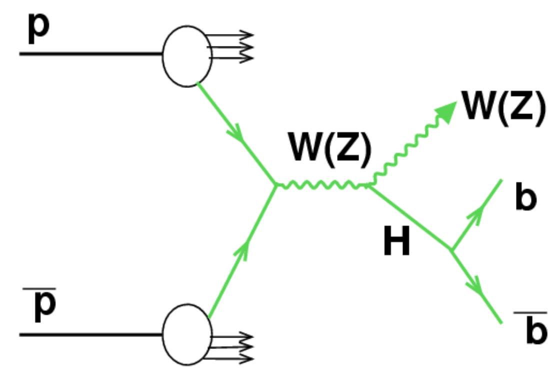
Clumpy: σ_{eff} is small and σ_{DP} is large

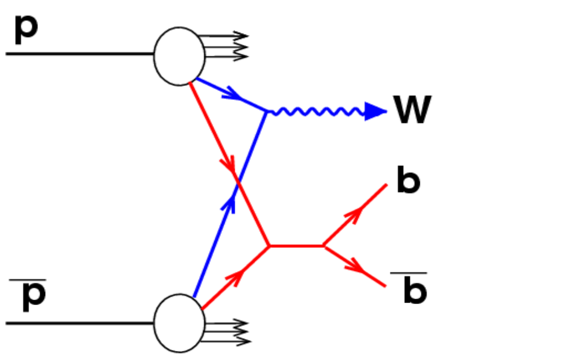
→ Needed for precise estimates of background to many rare processes (especially with multi-jet final state)

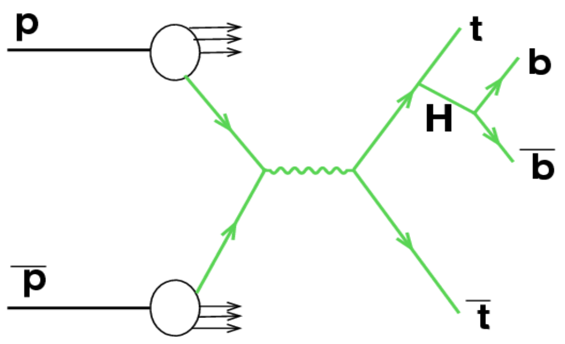
→ Should be measured in experiment !!

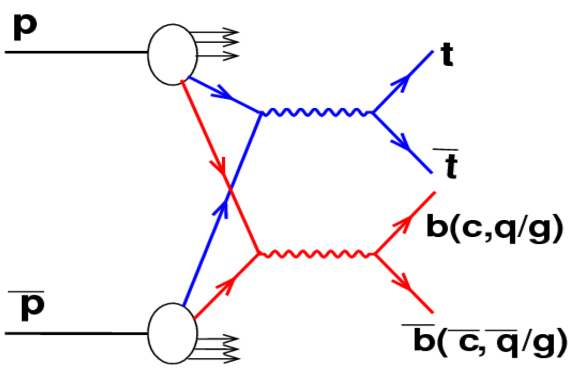
Double Parton events as a background to Higgs production

Signal | Double Parton background









- Many Higgs production channel can be mimicked by Double Parton event!
- Some of them can be significant even after signal selections.
- Dedicated cuts are required to increase sensitivity to the Higgs signal (same is true for many other rare processes)!

=> see example of possible variables below (and also 0911.5348[hep-ph])

Several estimates for LHC: PRD 61 077502; PRD 66 074012; arXiv:0710.0203

Previous Double Parton measurements

	$\sqrt{s}$ (GeV)	final state	p_T^{min} (GeV/c)	η range	Result
AFS, 1986	63	$4jets$	$p_T^{\rm jet} > 4$	$\|\eta^{jet}\| < 1$	$\sigma_{eff} \sim 5$ mb
UA2, 1991	630	$4jets$	$p_T^{\rm jet} > 15$	$\|\eta^{jet}\| < 2$	$\sigma_{eff} > 8.3$ mb (95% C.L.)
CDF, 1993	1800	$4jets$	$p_T^{\rm jet} > 25$	$\|\eta^{jet}\| < 3.5$	$\sigma_{eff} = 12.1^{+10.7}_{-5.4}$ mb
CDF, 1997	1800	$\gamma + 3jets$	$p_T^{\rm jet} > 6$	$\|\eta^{jet}\| < 3.5$	
			$p_T^{\gamma} > 16$	$\|\eta^{\gamma}\| < 0.9$	$\sigma_{eff} = 14.5 \pm 1.7^{+1.7}_{-2.3}$ mb

CDF 1997: photon+3jet events, **data-driven method**:
To extraxt $\sigma_{\rm eff}$: use of rates of events with Double Interaction (two separate $p\,\overline{p}$ collisions) and rates of Double Parton events from a single $p\,\overline{p}$ collision.

⇒ **reduce dependence on MC and NLO QCD theory predictions.**

Measurement of σ_{eff}

For two hard scattering events:

$$P_{DI} = 2\left(\frac{\sigma^{\gamma j}}{\sigma_{hard}}\right)\left(\frac{\sigma^{jj}}{\sigma_{hard}}\right)$$

The number of Double Interaction events:

$$N_{DI} = 2\frac{\sigma^{\gamma j}}{\sigma_{hard}}\frac{\sigma^{jj}}{\sigma_{hard}} N_C(2) A_{DI}\,\epsilon_{DI}\,\epsilon_{2vtx}$$

For one hard interaction:

$$P_{DP} = \left(\frac{\sigma^{\gamma j}}{\sigma_{hard}}\right)\left(\frac{\sigma^{jj}}{\sigma_{eff}}\right)$$

Then the number of Double Parton events:

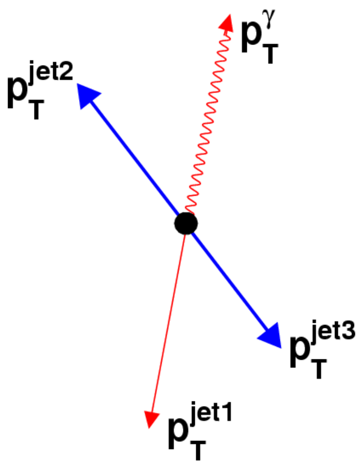
$$N_{DP} = \frac{\sigma^{\gamma j}}{\sigma_{hard}}\frac{\sigma^{jj}}{\sigma_{eff}} N_C(1) A_{DP}\,\epsilon_{DP}\,\epsilon_{1vtx}$$

Therefore one can extract:

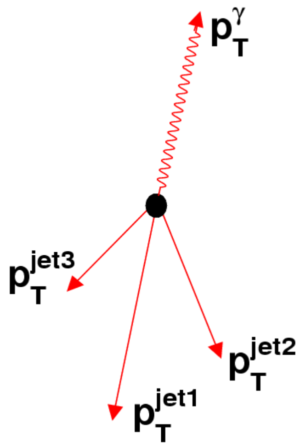
$$\sigma_{eff} = \frac{N_{DI}}{N_{DP}}\frac{N_C(1)}{2N_C(2)}\frac{A_{DP}}{A_{DI}}\frac{\epsilon_{DP}}{\epsilon_{DI}}\frac{\epsilon_{1vtx}}{\epsilon_{2vtx}}\sigma_{hard}$$

γ+3 jets events topology: Double Parton and Double Interaction events

DP



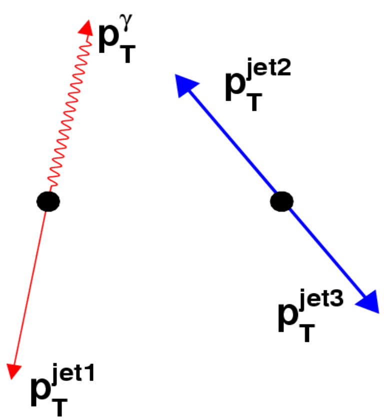
SP



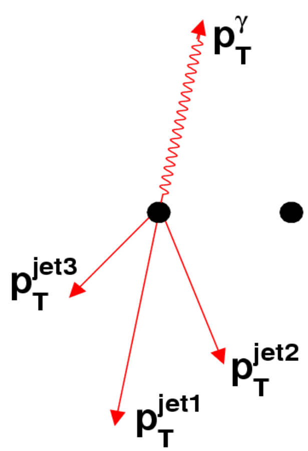
Signal: Double Parton (DP) production:
1st parton process produces γ-jet pair, while 2nd process produces dijet pair.

Background: Single Parton (SP) production:
single hard γ-jet scattering with 2 radiation jets in 1vertex events.

DI



SP

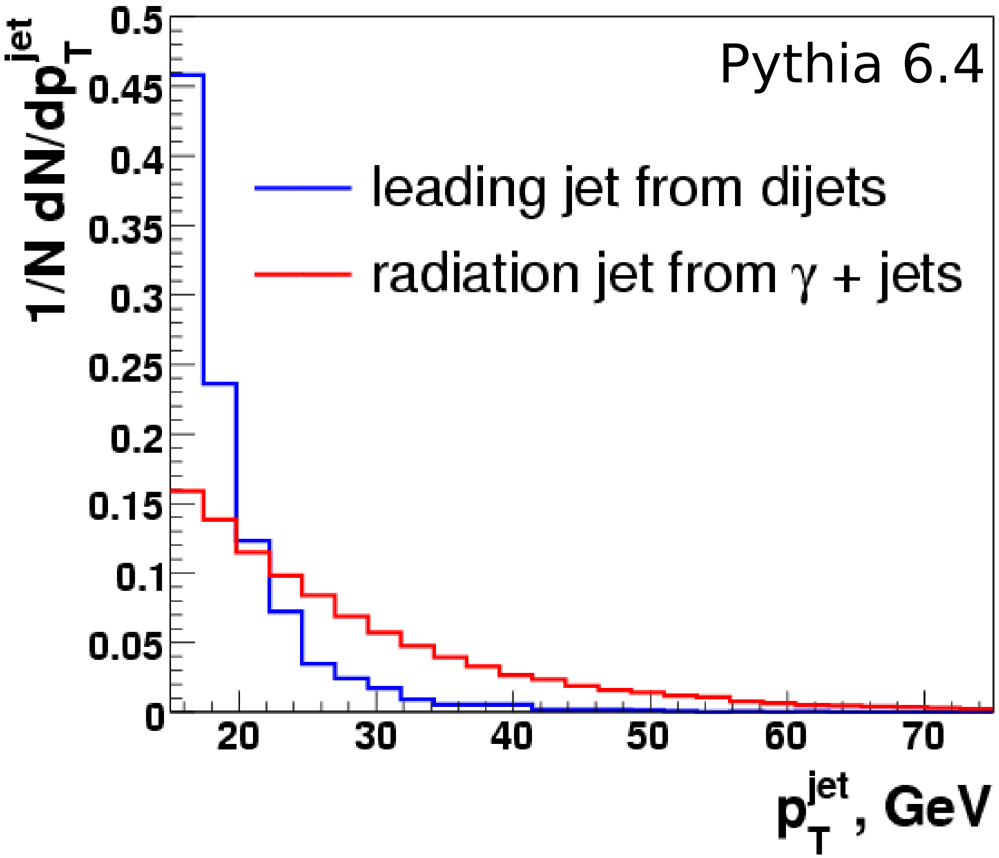


Background: Single Parton (SP) production:
single hard γ-jet scattering in one vertex with 2 radiation jets and soft unclustered energy in the 2nd vertex.

Signal: Double Interaction (DI)production:
two separate collisions within the same beam crossing, producing γ-jet and dijet pairs.

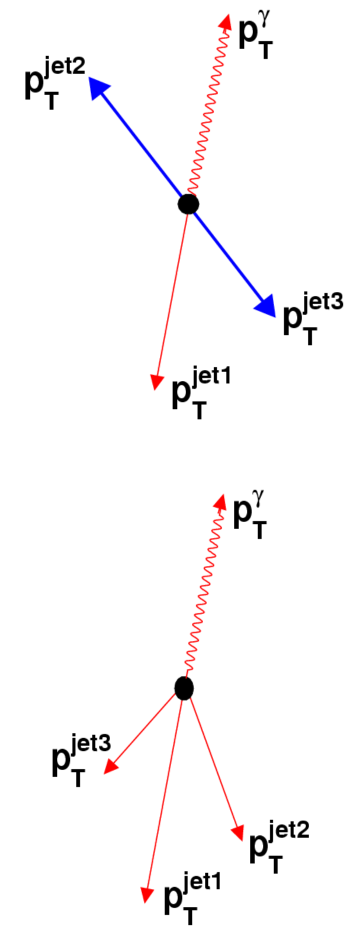
Motivation for jet pT binning

Jet PT: jet from dijets vs. radiation jet from γ+jet events



$\sim 1/p_T^4$

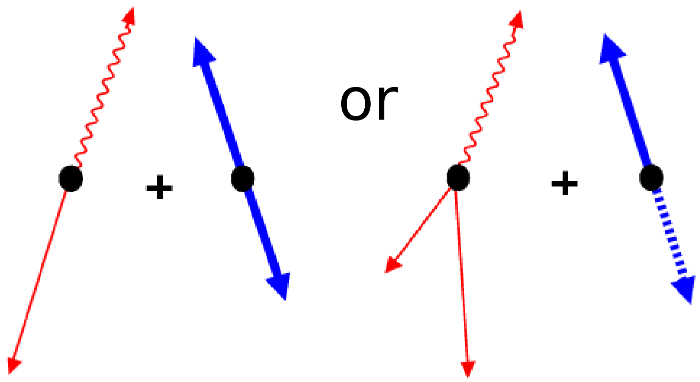
$\sim 1/p_T^2$



- Jet pT from dijets falls much faster than that for radiation jets, i.e.
  → Fraction of dijet (Double Parton) events should drop with increasing jet PT
  => Measurement is done in the three bins of 2nd jet pT: 15-20, 20-25, 25-30 GeV

Double Parton interaction model

Built from D0 data. Samples:



A: photon + ≥1 jet from γ+jets data events:
- 1-vertex events
- photon pT: 60-80 GeV
- leading jet pT>25 GeV, |η|<3.0.

B: ≥1 jets from MinBias events:
- 1-vertex events
- jets with pT's recalculated to the primary vertex of sample A have pT>15 GeV and |η|<3.0.

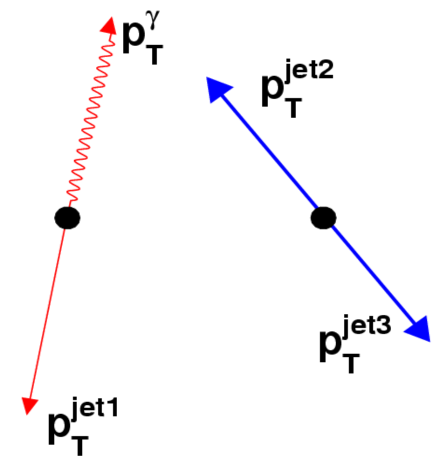
- **A** & **B** samples have been (randomly) mixed with jets pT re-ordering
- Events should satisfy photon+≥3 jets requirement.
- △R(photon, jet1, jet2, jet3)>0.7

⇨ Two scatterings are independent by construction

Double $p\bar{p}$ Interaction model

Built from D0 data by analogy to Double Parton model with the only difference: ingredient events (γ+jets and dijets) are 2-vertex events.

In case of 2 jets, both jets are required to originate from the Primary Vertex using jet track information.

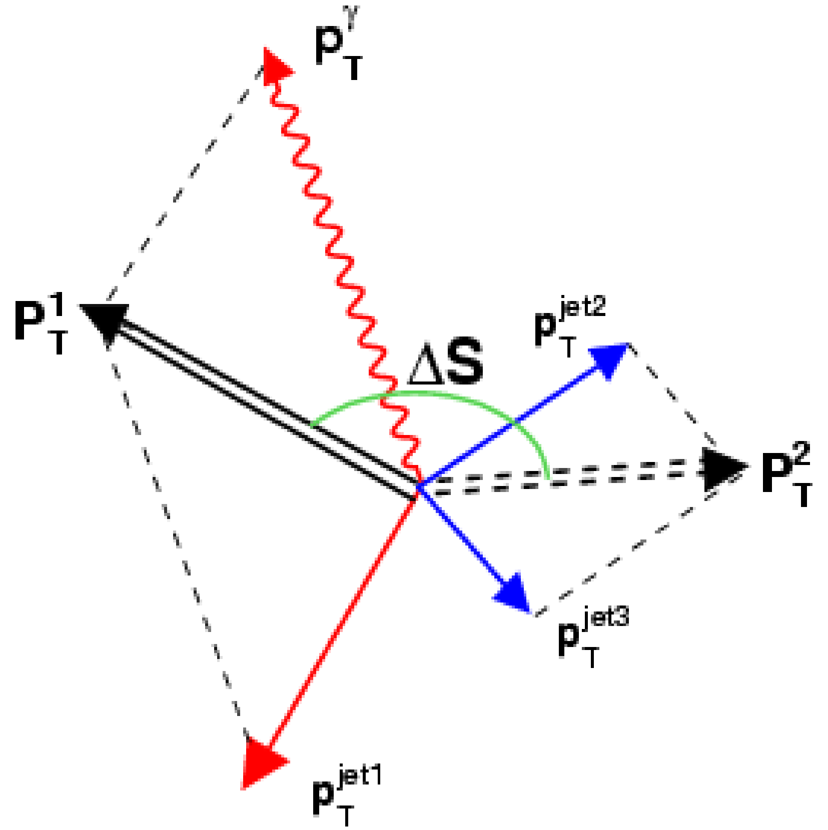


⇨ Main difference of Double Parton and Double $p\bar{p}$ Interaction signal events and corresponding SP backgrounds: different amount of soft unclustered energy in 1-vertex vs. 2-vertex events.

Discriminating variables

$$\Delta S = \Delta\phi(p_T^{\gamma,\,\text{jet}}, p_T^{\text{jet}_i,\,\text{jet}_k})$$

- $\Delta\phi$ angle between two best pT-balancing pairs →
- The pairs should correspond to a minimum S value:

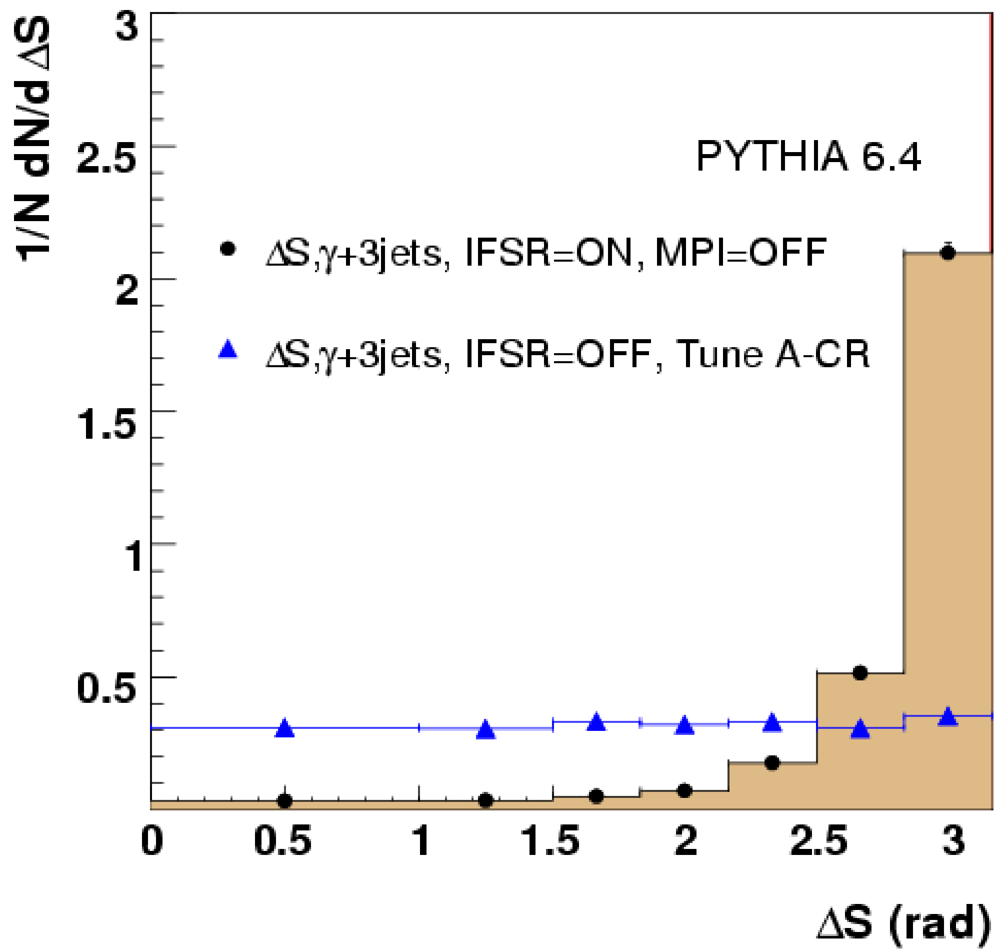


$$S_\phi = \frac{1}{\sqrt{2}}\sqrt{\left(\frac{\Delta\phi(\gamma,i)}{\delta\phi(\gamma,i)}\right)^2 + \left(\frac{\Delta\phi(j,k)}{\delta\phi(j,k)}\right)^2}$$

$$S_{p_T} = \frac{1}{\sqrt{2}}\sqrt{\left(\frac{|\vec{P_T}(\gamma,i)|}{\delta P_T(\gamma,i)}\right)^2 + \left(\frac{|\vec{P_T}(j,k)|}{\delta P_T(j,k)}\right)^2}$$

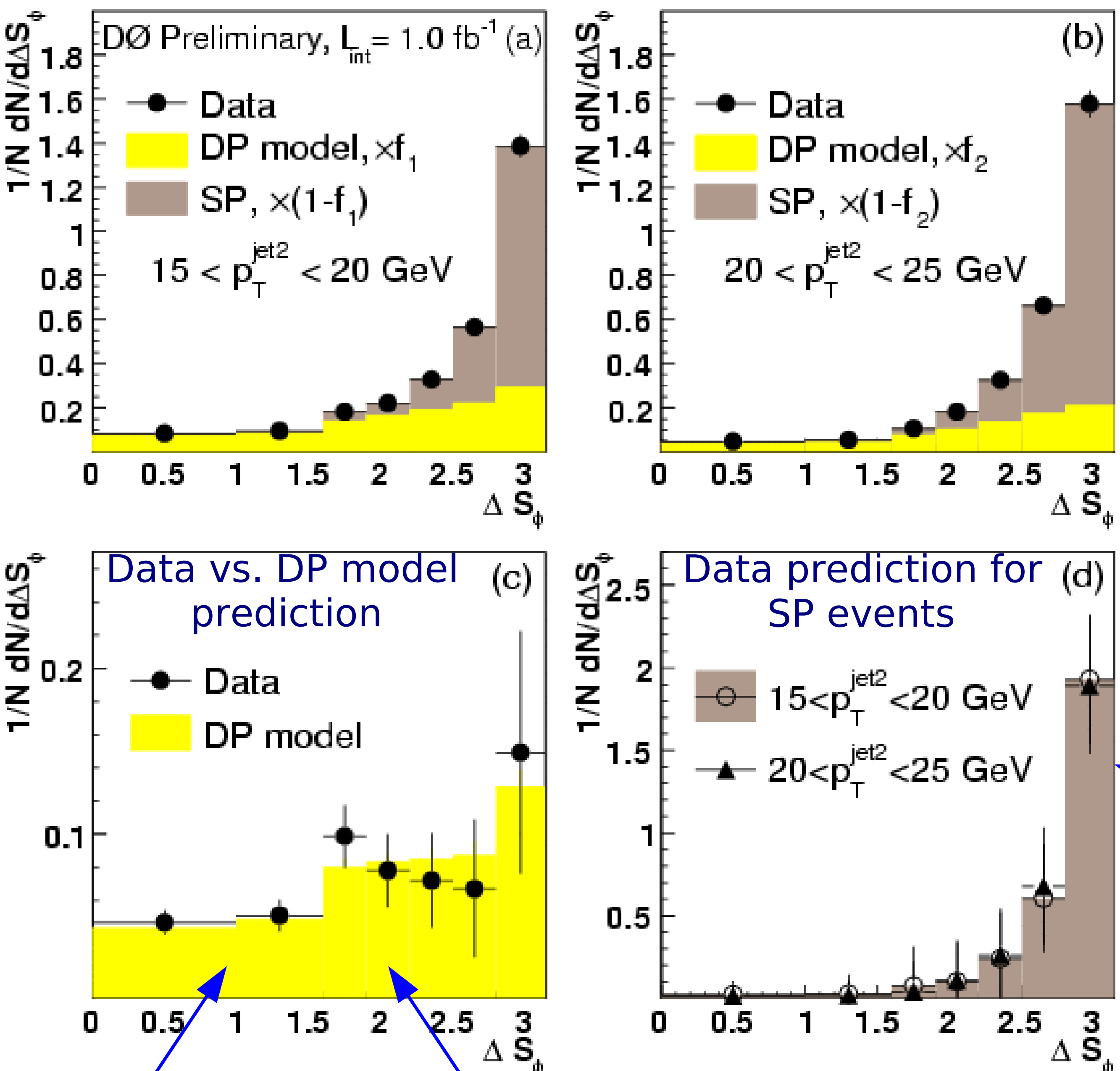
In the signal sample most likely (>94%) S-variables are minimized by pairing photon with the leading jet.

$\triangle$S distribution for γ+3jets events from Single Parton scattering



➔ For "γ+3jets" events from Single Parton scattering we expect ΔS to peak at π, while it should be flat for "ideal" Double Parton interaction (2^{nd} and 3^{rd} jets are from dijet production).

The two datasets method



Dataset (a): 2nd jet pT: 15-20 GeV
Dataset (b): 2nd jet pT: 20-25 GeV

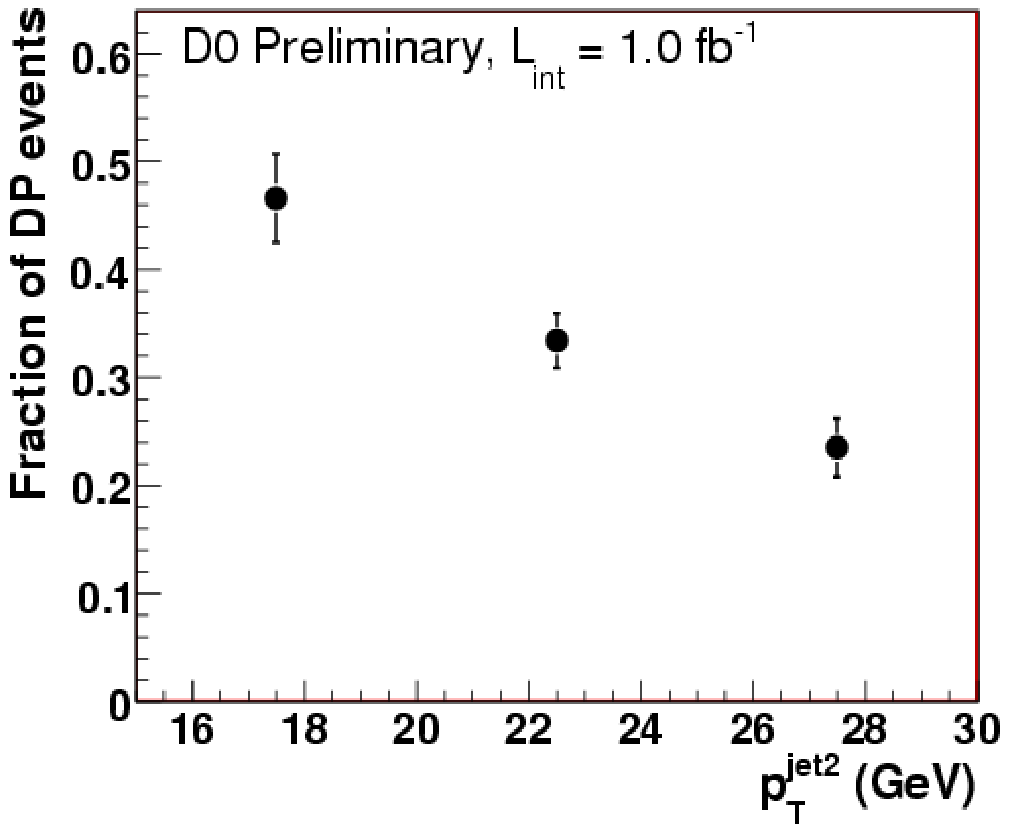
✓Fraction of Double Parton in bin 15-20 GeV (f_1) is the only unknown
→ get from minimization.

✓Good agreement of the ΔS Single Parton distribution extracted in data and in MC (see previous slide)
→another confirmation for the found DP fractions.

Data are corrected for the DP fractions

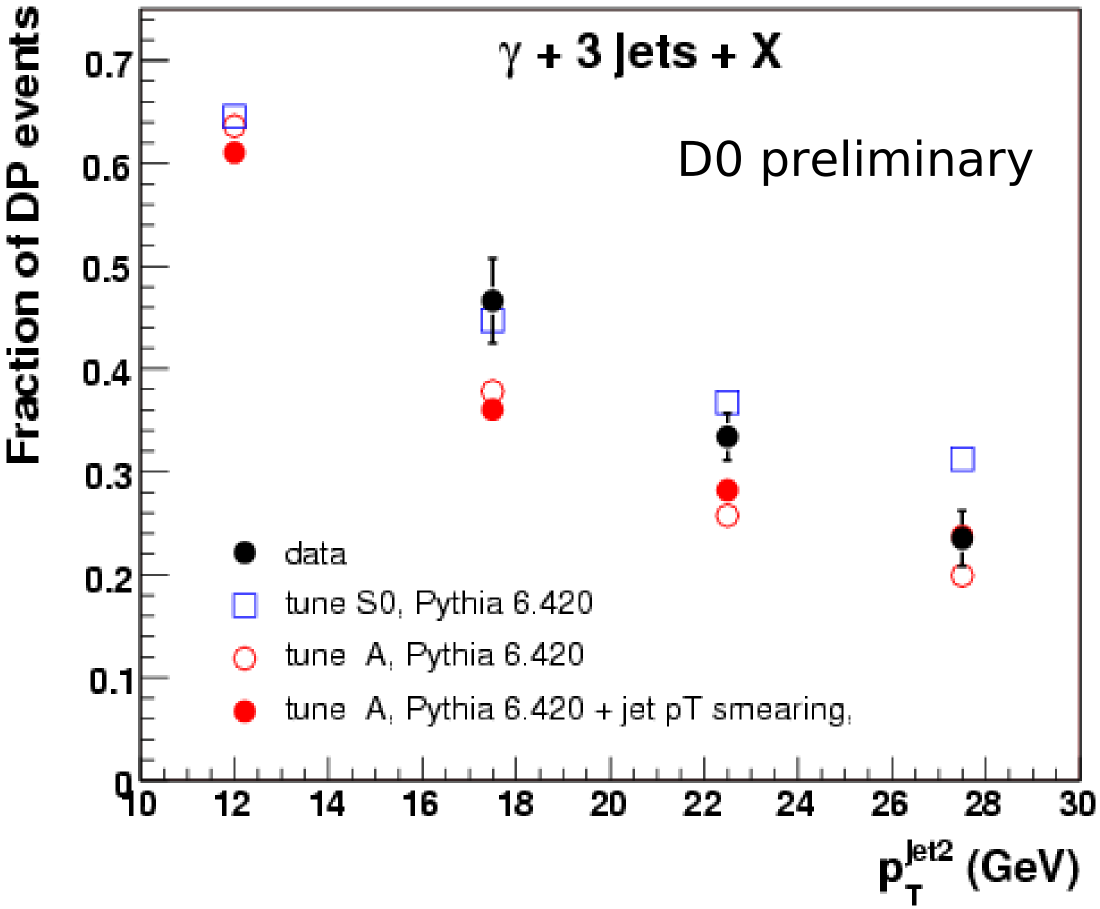
✓Good agreement of Data and DP model

Fractions of Double Parton events



Fractions drop from ~46-48% at 2nd jet 15<pT<20 GeV to ~22-23% at 2nd jet 25<pT<30 GeV with relative uncertainties ~7-12%.

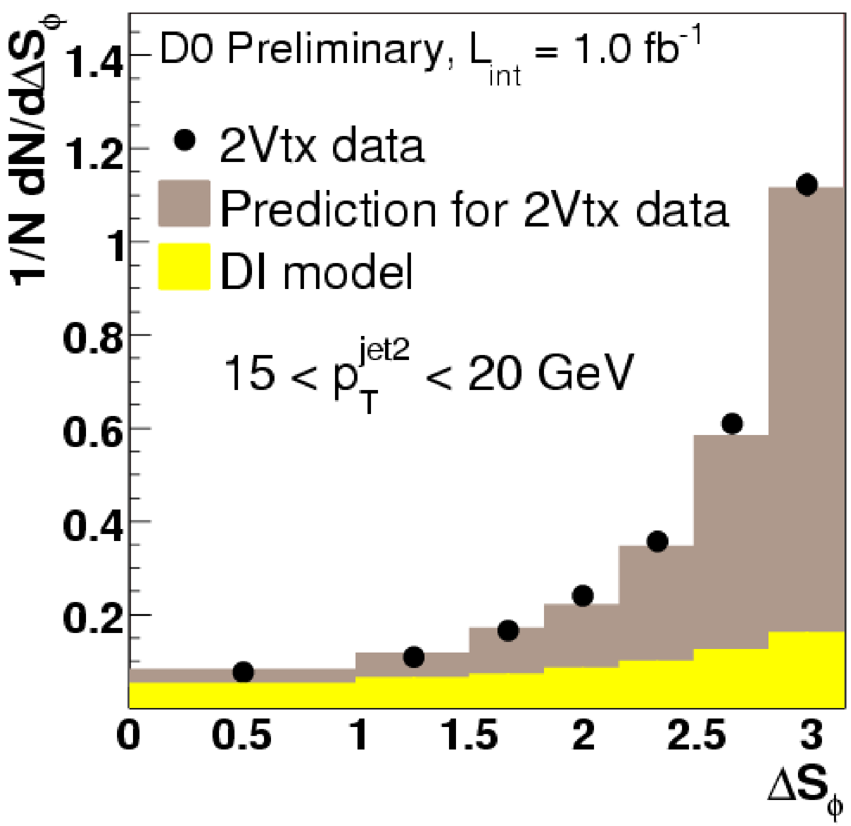
Fractions of Double Parton events : MPI models and D0 data

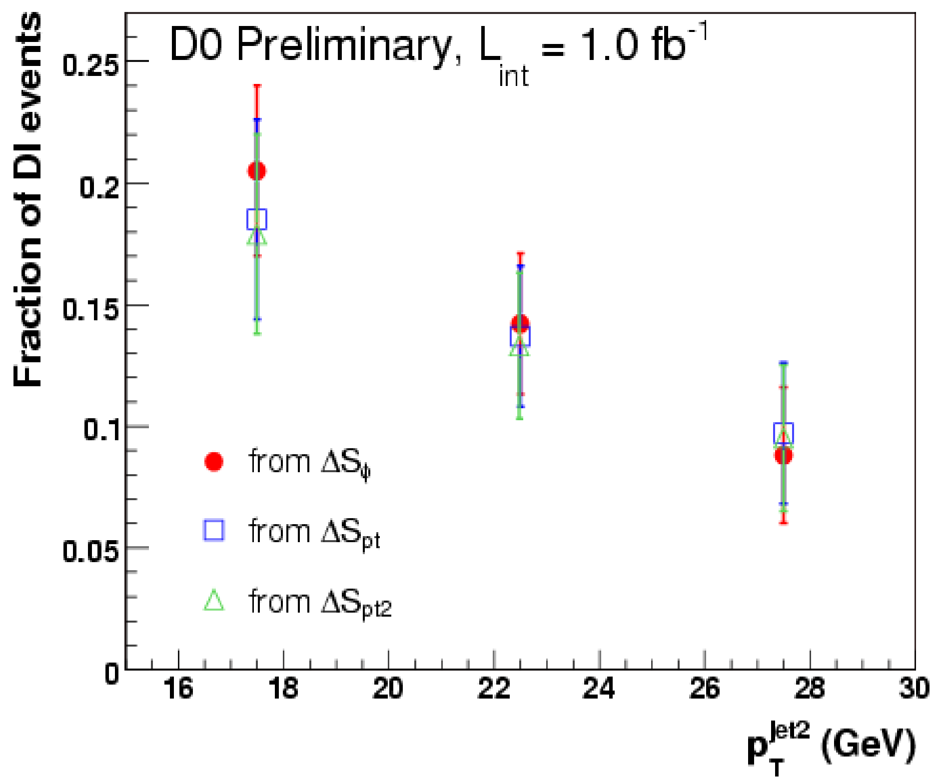


- Pythia MPI tunes A and S0 are considered.
- Data are in between the model predictions.
- Results are preliminary: data should be corrected to the particle level.
- Will be done later to find the best MPI Tune

Fractions of Double $p\,\bar{p}$ Interactions (DI) events

To calculate σ_{eff}, we also need $N_{DI} = f_{DI}\ N_{2vtx}$.
→ use ΔS shapes and get f_{DI} by fitting DI signal and background distributions to 2-vertex data





Total sum of DI signal+bkgd, weighted with DI fractions, is in agreement with data

Main uncertainties in DI fractions are from building DI signal and background models

Calculation of Nc(n) and σ_{hard}

Total numbers of events with 1 and 2 hard $p\bar{p}$ collisions, Nc(1) and Nc(2), are calculated from the expected average number of hard interactions at a given instantaneous luminosity L_{inst}:

$$\bar{n} = \left(L_{inst}/f_0\right)\sigma_{hard}$$

using Poisson statistics.

f_0 is a frequency of the beam crossings at the Tevatron in RunII.

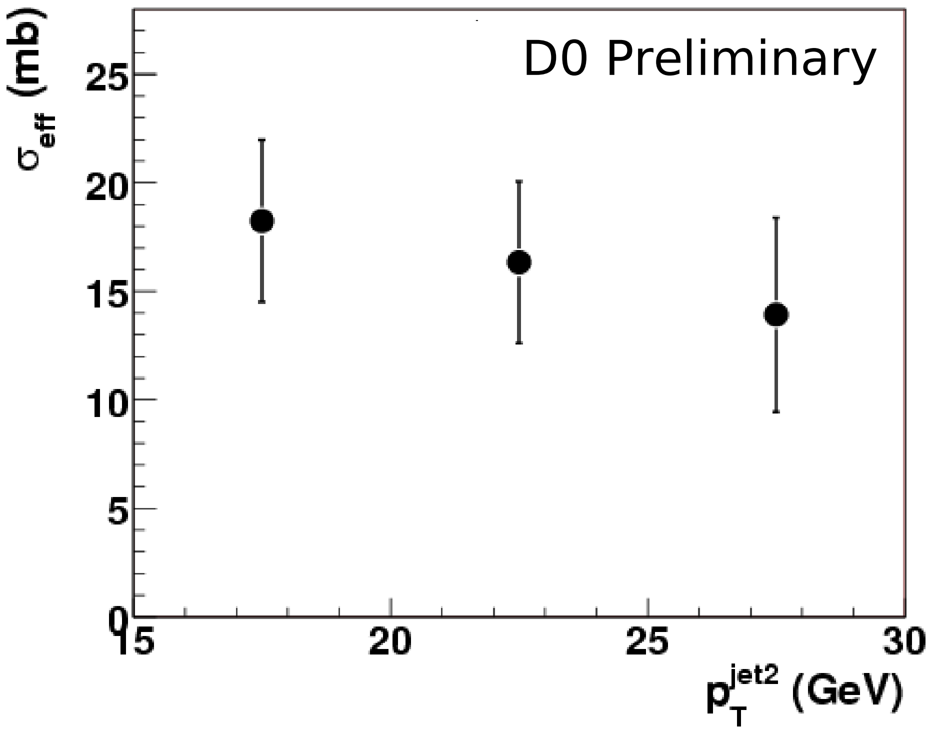
σ_{hard} is hard (non-elastic, non-diffractive) $p\bar{p}$ cross section.

It is 44.7 ± 2.9 mb : from Run I → Run II extrapolation.

$$R_C = \frac{N_C(1)}{2N_C(2)}\sigma_{hard} = 52.3\,mb$$

Variation of σ_{hard} within uncertainty (2.9 mb) gives the uncertainty for Rc of just about 1.0 mb: increase of σ_{hard} leads to decrease of Nc(1)/Nc(2) and vice versa.

Calculation of σ_{eff}



- σ_{eff} values in different jet pT bins agree with each other within their uncertainties (also compatible with a slow decrease with pT).

- Uncertainties have very small correlations between jet2 pT bins.
- One can calculate the averaged (weighted by uncertainties) values over jet2 pT bins:

$$\sigma_{eff}^{ave} = 16.4 \pm 0.3 (stat) \pm 2.3 (syst)\, mb$$

Main systematic and statistical uncertainties (in %) for σ_{eff}.

p_T^{jet2} (GeV)	Systematic uncertainty sources f_{DP}	f_{DI}	$\varepsilon_{DP}/\varepsilon_{DI}$	JES	$R_c\sigma_{hard}$	δ_{syst} (%)	δ_{stat} (%)	δ_{total} (%)
15 – 20	7.9	17.1	5.6	5.5	2.0	20.5	3.1	20.7
20 – 25	6.0	20.9	6.2	2.0	2.0	22.8	2.5	22.9
25 – 30	10.9	29.4	6.5	3.0	2.0	32.2	2.7	32.3

Summary (1)

We have measured:

- Fraction of Double Parton events in three pT bins of 2nd jet : 15-20, 20-25, 25-30 GeV. It varies from about 0.47 at 15-20 GeV to 0.22 at 25-30 GeV.

- Effective cross section (process-independent, defines rate of Double Parton events) σ_{eff} has been measured in the same jet pT bins with average value:

$$\sigma_{eff}^{ave} = 16.4 \pm 0.3(stat) \pm 2.3(syst)\, mb$$

- The found σ_{eff} is in the range of those found in CDF measurements at lower scales
  → it might indicate a stable behaviour w.r.t. the energy scales in the parton scatterings.

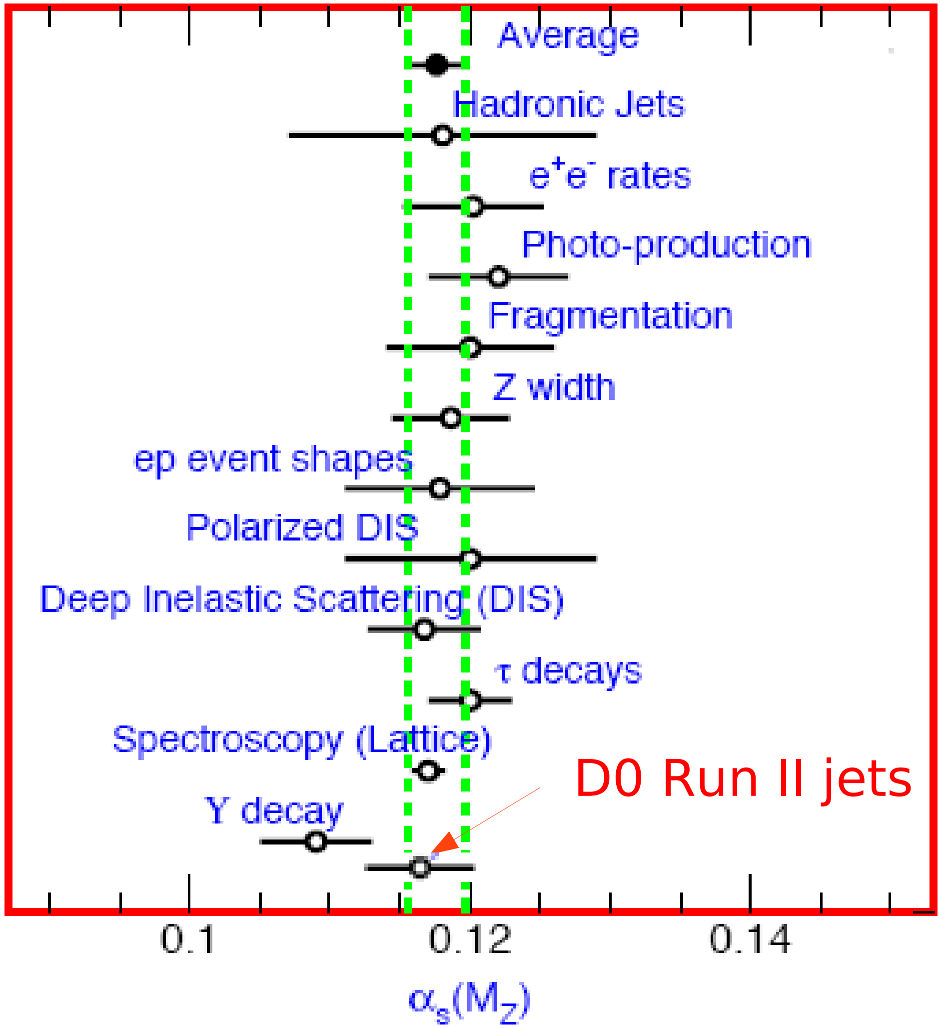
- Double Parton production can be a significant background to many rare processes, especially with multi-jet final state. A choice of the dedicated variables is advised. It also necessitates tuning of MC generators, for which these results should be very helpful.

Summary (2)

New α_s result from Tevatron inclusive jet pT cross sections

$$\alpha_s(M_Z) = 0.1161^{+0.0041}_{-0.0048}$$

- → Considerable improvement in comparison with accuracy of Run I jet result
- → Similar precision as HERA jets (0.1189 ±0.0032)
- → Good agreement with the world average: 0.1184 ± 0.0007



BACK-UP SLIDES

Comparison of γ+3 jets measurements: CDF'97 vs. D0'09

- ✓ Center of mass energy : 1.8 → 1.96 TeV

- ✓ About a factor 60 increase in the intergrated luminosity allows to change selections:
  photon pT > 16 GeV (CDF) → 60 < pT < 80 GeV (D0)
  ⇨ A better separation of 2 partonic scatterings in the momentum space
  ⇨ A higher photon purity (due to also tighter photon ID)
  ⇨ A better determination of energy scales of 1st parton process

- ✓ Higher jet pTs and JES correction to the particle level
  Jet pT (uncorr.) > 6 GeV → pT (corr.) > 15 GeV

- ✓ Binning in the 2nd jet pT : 15 - 20; 20 - 25, 25 – 30 GeV
  ⇨ A better determination of energy scales of 2nd process
  ⇨ Study of Double Parton fractions and σ_{eff} vs. 2nd jet pT

- ✓ Double Parton fractions and σ_{eff} are inclusive: we do not subtract fractions of events with triple parton interactions.

PDF correlations and σ_{eff}

- Correlations between PDFs are possible and may even *increase* DP cross section at large (≥W/Z mass) factorization scales (10-40%!):
  - A.M. Snigirev et al : PRD68 (2003)114012, PLB 594(2004)171
  - D. Treleani et al : PRD72 (2005)034032

- Direct account of PDFs is in DP PDF (!): *first* evolution equations for dPDF (extension of sPDF) --> J.Gaunt and J.Stirling, 0910.4347 [hep-ph]

dDGLAP evolution:

if the two-parton distributions are factorized at some scale μ_0

$G(x_1,x_2,\mu_0) = G(x_1,\mu_0)^*G(x_2,\mu_0)$

then the evolution violates this factorization *inevitably* at any diff. scale $\mu \neq \mu_0$:

$G(x_1,x_2,\mu) = G(x_1,\mu)^*G(x_2,\mu) + R(x_1,x_2,\mu)$

where $R(x_1,x_2,\mu)$ is a correlation term.

$$d\sigma = \sum_{q/g} \int \frac{d\sigma_{12} d\sigma_{34}}{2\sigma_{\text{eff}}} D_p(x_1,x_3) D_{\bar{p}}(x_2,x_4) dx_1 dx_2 dx_3 dx_4$$

⇩

$$\frac{\sigma_{DPS}^{\gamma+3j}}{\sigma^{\gamma j}\sigma^{jj}} = [\sigma_{\text{eff}}^{\text{exp}}]^{-1} \quad \Rightarrow \quad [\sigma_{eff}^{\text{exp}}]^{-1} = [\sigma_{eff}]^{-1}(1+\delta(\mu))$$

Models of parton spatial density and σ_{eff}

- σ_{eff} is directly related with parameters of models of parton spatial density
- Three models have been considered: Solid sphere, Gaussian and Exponential.

TABLE VI: Parameters of parton spatial density models calculated from measured σ_{eff}.

Model for density	$\rho(r)$	σ_{eff}	R_{rms}	Parameter (fm)	R_{rms} (fm)
Solid Sphere	Constant, $r < r_p$	$4\pi r_p^2/2.2$	$\sqrt{3/5}r_p$	0.53 ± 0.06	0.41 ± 0.05
Gaussian	$e^{-r^2/2a^2}$	$8\pi a^2$	$\sqrt{3}a$	0.26 ± 0.03	0.44 ± 0.05
Exponential	$e^{-r/b}$	$28\pi b^2$	$\sqrt{12}b$	0.14 ± 0.02	0.47 ± 0.06

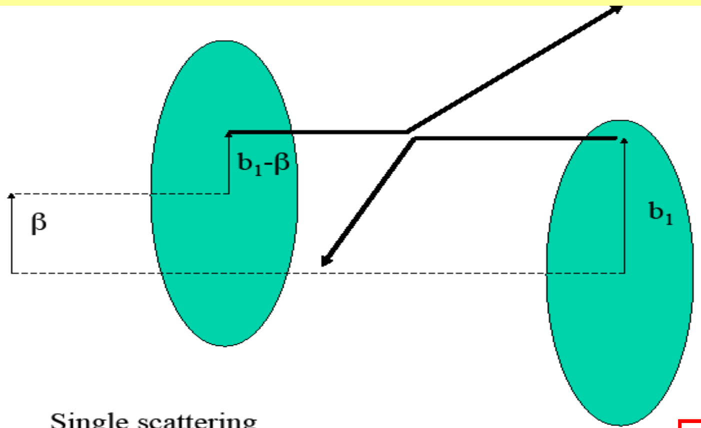
– The rms-radia above are calculated w/o account of possible parton spatial correlations. For example, for the Gaussian model one can write [Trleani, Galucci, 0901.3089,hep-ph]:

$$\frac{1}{\sigma_{eff}} = \frac{3}{8\pi R_{rms}^2}(1 + Corr.)$$

- If we have rms-radia from some other source, one can estimate the size of the spatial correlations

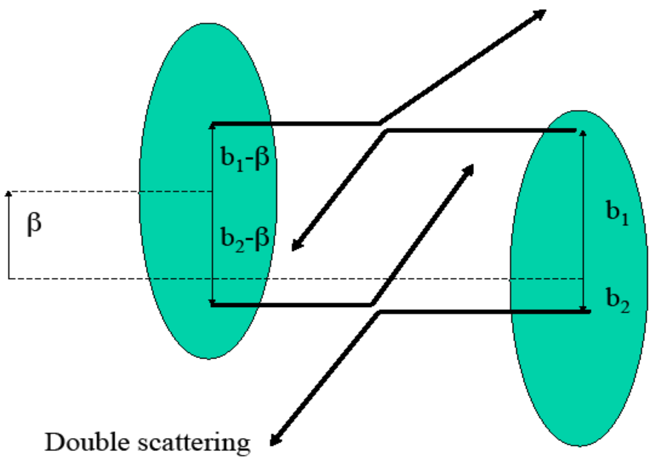
Parton spatial density and σ_{eff}

Introducing the 3D parton density $\Gamma(x,b)$ and making the assumption $\Gamma(x,b)=G(x)f(b)$ one may express the single scattering inclusive cross section as



Single scattering

$$\begin{aligned}\sigma_S &= \int_{p_t^c} G(x)\hat\sigma(x,x')G(x')dxdx' \\ &= \int_{p_t^c} G(x)f(b)\hat\sigma(x,x')G(x')f(b-\beta)d^2bdxdx'd^2\beta\end{aligned}$$



Double scattering

$$\begin{aligned}\sigma_D &= \frac{1}{2!}\int_{p_t^c} G(x_1)f(b_1)\hat\sigma(x_1,x_1')G(x_1')f(b_1-\beta)d^2b_1dx_1dx_1' \times \\ &\quad \times G(x_2)f(b_2)\hat\sigma(x_2,x_2')G(x_2')f(b_2-\beta)d^2b_2dx_2dx_2'd^2\beta \\ &= \frac{1}{2!}\int\Big(\int_{p_t^c} G(x)f(b)\hat\sigma(x,x')G(x')f(b-\beta)d^2bdxdx'\Big)^2 d^2\beta \\ &= \frac{1}{2}\frac{\sigma_S^2}{\sigma_{eff}}\end{aligned}$$

where $\sigma_{eff}^{-1} = \int d^2\beta\,[F(\beta)]^2$ is effective cross section

$$F(\beta) = \int f(b)f(b-\beta)d^2b,$$

and *f(b)* is the density of partons in transverse space.

1^{st} and 2^{nd} interactions: Estimates of possible correlations

... in the momentum space:

1st interaction: photon pT $\simeq$ 70 GeV, $\Rightarrow$ parton *xT* $\simeq$ *0.07*
2nd interaction: jet pT $\simeq$ 20 GeV, $\Rightarrow$ parton *xT* $\simeq$ *0.02*

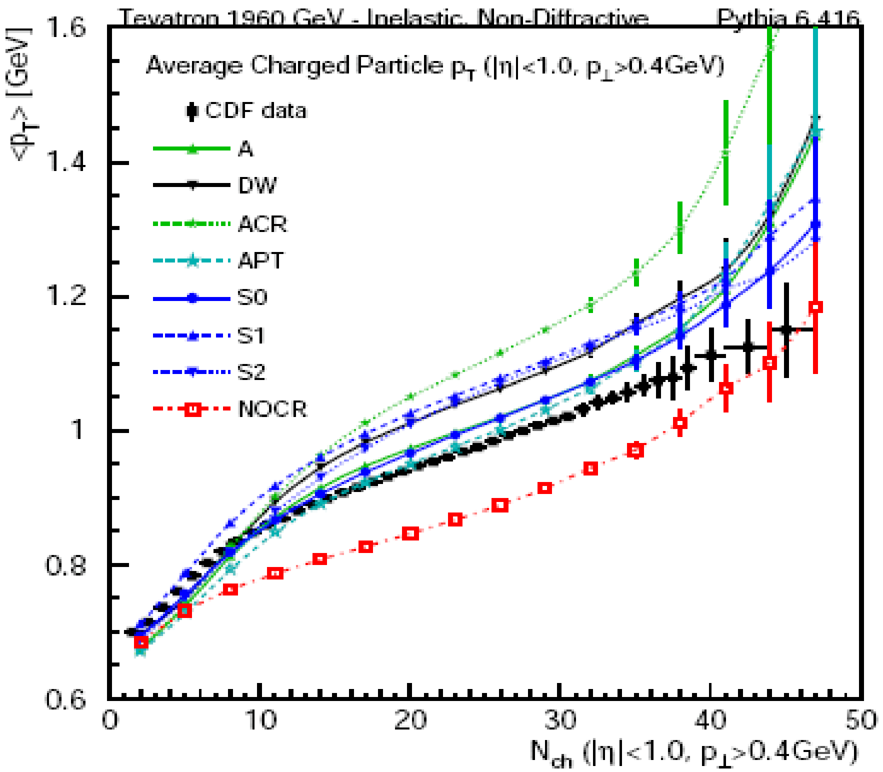
➲ large (almost unlimitted) kinematic space for the 2^{nd} interaction

... at the fragmentation stage :

=> Simulate γ+3 jets and di-jets with switched off ISR/FSR; then additional 2 jets in γ+3 jets should be from 2^{nd} parton interaction

=> compare 2^{nd} (3^{rd}) jets pT/Eta in γ+3 jets with 1^{st} (2^{nd})jet pT/Eta in dijets

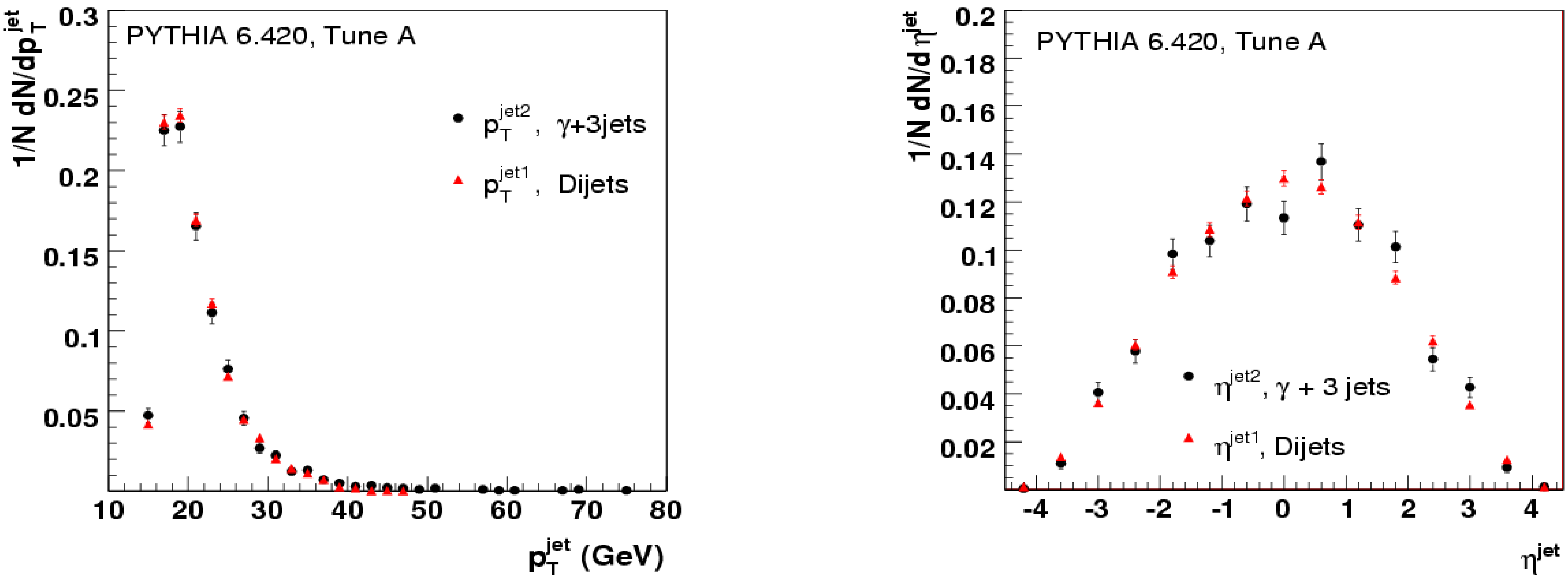
=>Tunes tested: A, A-CR, S0



From D.Wicke & P.Skands
hep-ph:0807.3248

γ+3 jets and di-jets, IFSR=OFF: jets pT comparison.

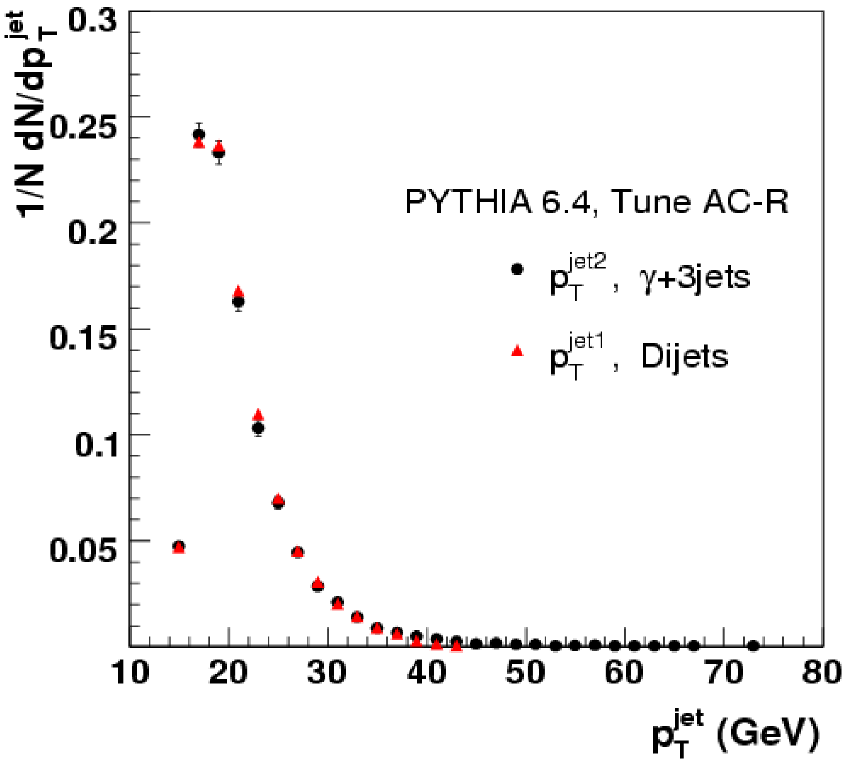
Tune A

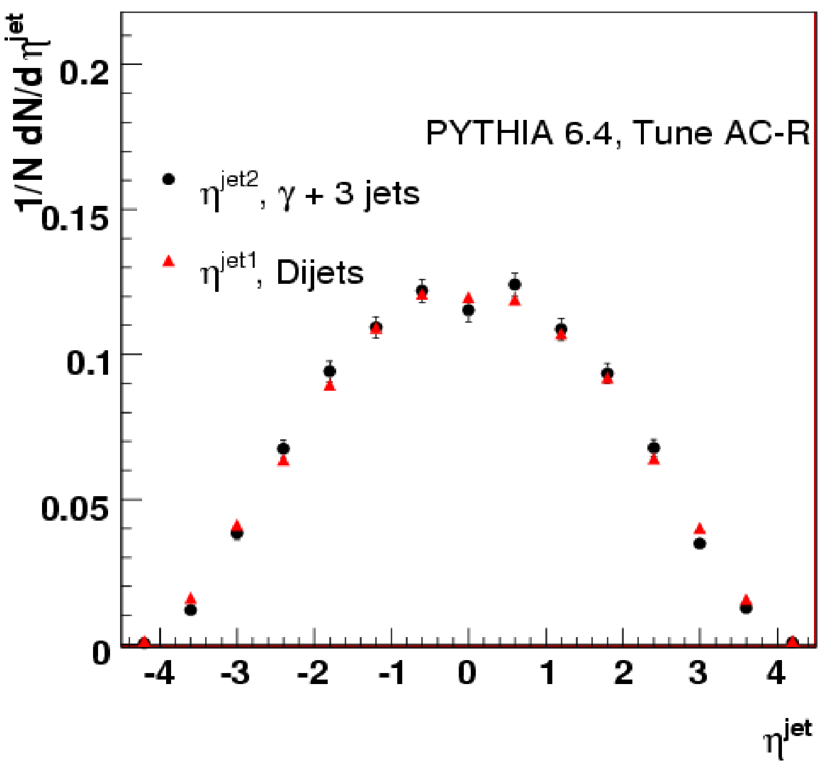


- pT and Eta distributions are analogous for jets from 2nd interaction in γ+3jets and di-jet events
- Analogous results (incl. 3rd jet from γ+3jets and 2nd from di-jets) are obtained for Tunes A-CR, S0.

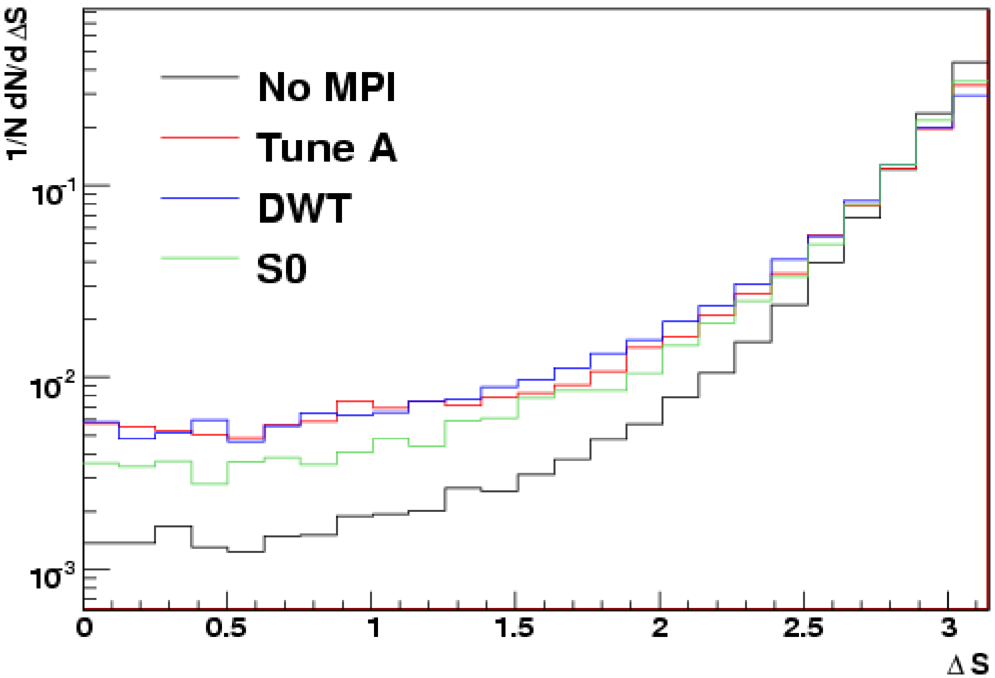
γ+3 jets and di-jets, IFSR=OFF: jets pT comparison.

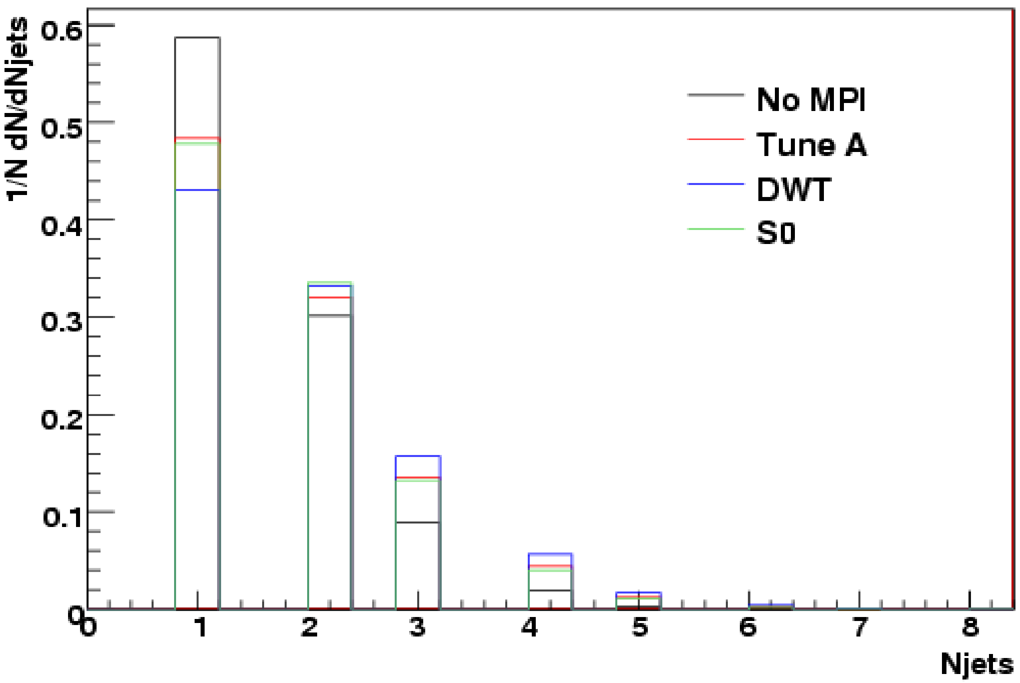
Tune A-CR





Pythia MPI Tunes: ΔS and Njets

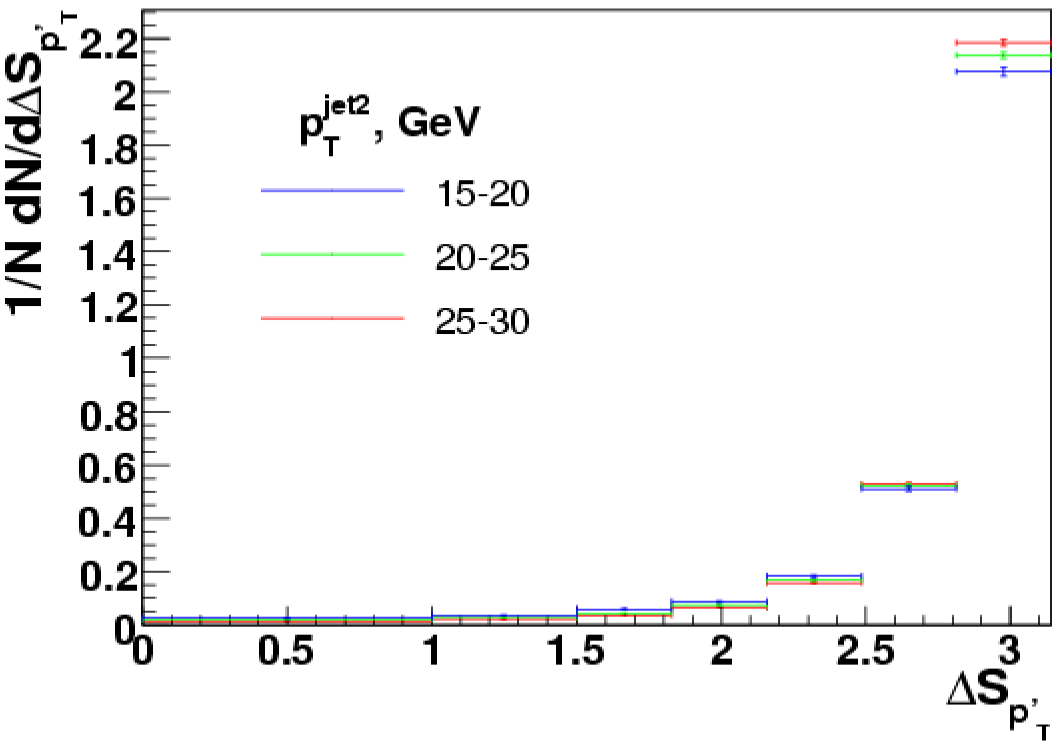


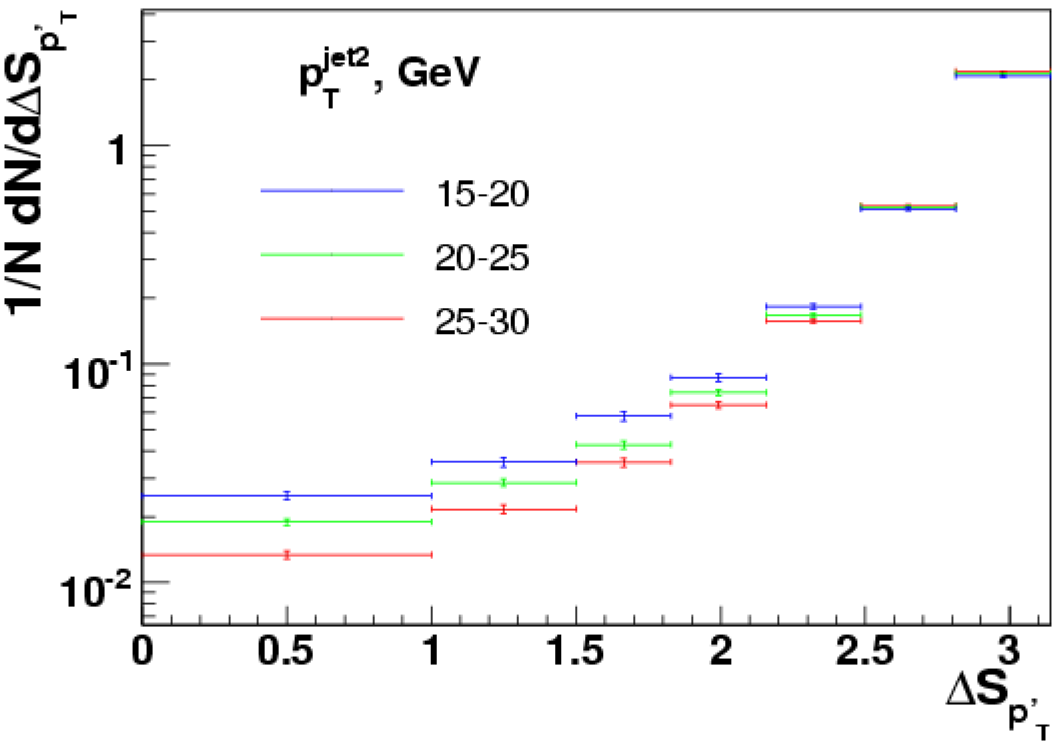


Pythia predictions with MPI tunes:

- ΔS is much broader for events with MPI events and almost flat at ΔS < 1.5
- #events(Njest≥1) / #events(Njets≥3) is larger by a factor 2(!) for MPI events

SP events (Pythia): ΔS distributions





SELECTION CRITERIA

VERTEX:

- $|Z|<60$cm,
- Ntrk>=3

JETS (pT corrected):

- Midpoint Cone algo with R=0.7
- $|\eta|<3.0$
- #jets ≥ 3
- pT of any jet > 15 GeV
- pT of leading jet > 25 GeV
- pT of 2nd jet∈(15,20), (20,25), (25,30) GeV.

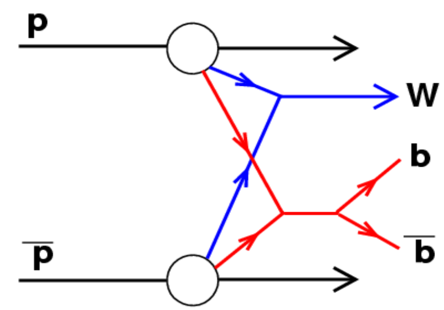
PHOTONS:

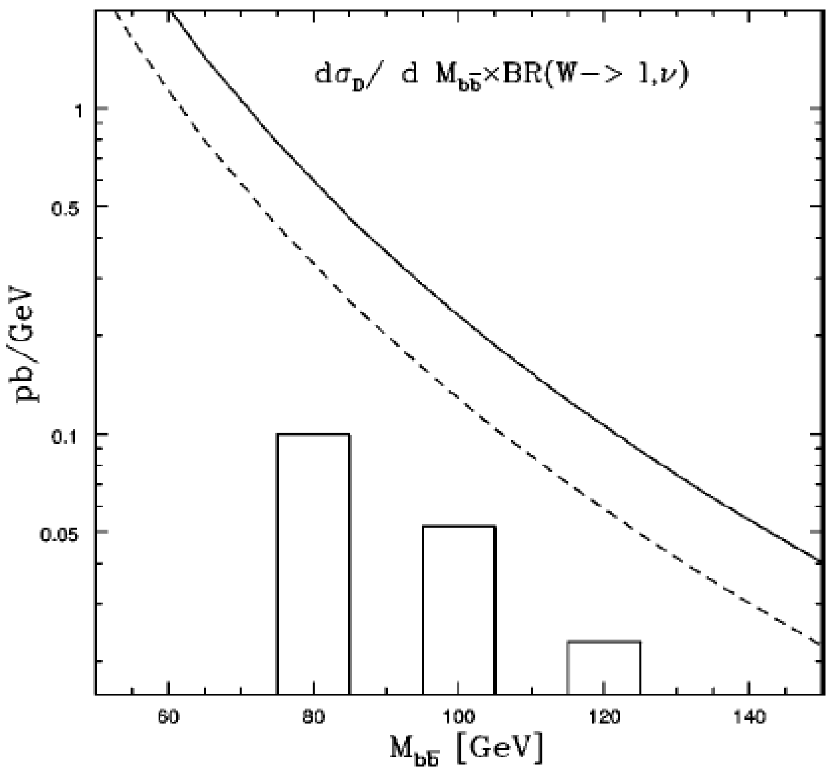
- photons with $|\eta|<1.0$ and $1.5<|\eta|< 2.5$
- 60< pT< 80 GeV (good separation of 1st and 2nd parton interactions)
- Shower shape cuts
- Calo isolation (0.2< dR <0.4) < 0.07
- Track isolation (0.05< dR <0.4) < 1.5 GeV
- Track matching probability < 0.001

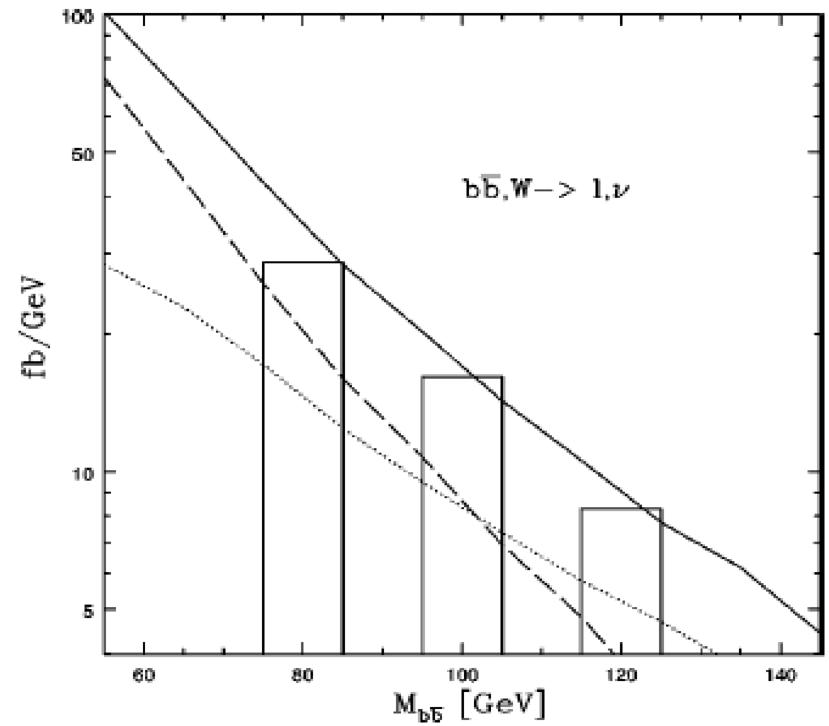
- ΔR(any objects pair)>0.7

Example: DP as a background to p + p → WH (LHC)

From PRD61, Fabbro, Treleani (2000)





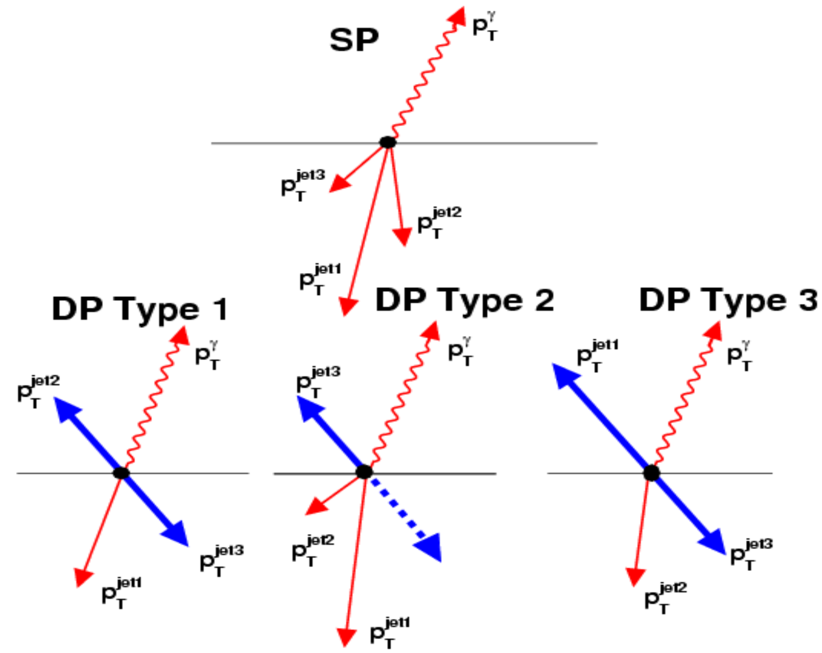


DP background as a function of H mass:
LO and NLO bb production
(σ_{eff} = 14.5 mb used here)
DP background is 3 orders of magnitude higher than the HW cross section

SM/SP (dotted) and DP (dashed) cross sections after selection cuts
DP background is still very important even after selections

Fractions of MixDP event types

Event Types	$p_T^{\rm jet2}$ (GeV)		
	$15-20$	$20-25$	$25-30$
Type I	0.261	0.217	0.135
Type II	0.729	0.778	0.861
Type III	0.010	0.005	0.004



- Type II events (1 jet from dijet and 1 brems. jet) dominate (≥73%): It is caused by jet reco eff-cy and threshold (6 GeV for pT_raw) and difference in jet pT (it is smaller for dijets)
- CDF ('97) found at least 75% Type II events: a good agreement.
- Small fraction of Type III events.
- Important: dominance of Type II naturally reduces a dependence of results (see variable ΔS below) on possible issues with correlations between 1st & 2nd parton interactions.

The fraction of DP events: the two datasets method

Since dijet pT cross section drops faster than that of radiation jets the different DP fractions in various (2nd) jet pT intervals are expected. The larger 2nd jet pT the smaller DP fraction.

Dataset 1 - “DP-rich”, smaller 2nd jet pT bin, e.g. 15-20 GeV
Dataset 2 - “DP-poor”, larger 2nd jet pT bin, e.g. 20-25 GeV

Each distribution can be expressed as a sum of DP and SP :

$$D_1 = f_1 M_1 + (1 - f_1) B_1$$

$$D_2 = f_2 M_2 + (1 - f_2) B_2$$

D_i - data distribution
M_i - MIXDP distribution
B_i - background distribution
f_i - fraction of DP events
$(1 - f_i)$ - fraction of SP events

$$D_1 - f_1 M_1 = (1 - f_1) B_1$$

$$D_2 - f_2 M_2 = (1 - f_2) B_2$$

From SP MC

From MixDP

$$D_1 - \lambda K D_2 = f_1 M_1 - \lambda K C f_1 M_2$$ where $$\lambda = \frac{B_1}{B_2} \quad K = \frac{(1 - f_1)}{(1 - f_2)} \quad C = \frac{f_2}{f_1}$$

f_1 is the only unknown, --> get from minimization

Some History

Theoretical discussion on DPS continues for many years (~end of 1970's)

– Simple models of double di-jet double Drell-Yan productions by
  - P.V.Landshoff and J.C. Polkinghorne - 1978
  - C.Goebel et al - 1980
  - B.Humpert et al - 1983-85
  - L.Ametller, N.Paver, D.Treleani - 1982-1986
  - E. Takagi (MPI in pN interactions) - 1979
  - ....

– T. Sjostrand and M.van Zijl: PRD36 (1987)2019 – first real, software-implemented MPI model, known as “Tune A”(updated by R.Field). Description of many “puzzling features” of jet production (#track, jet shapes, #jets, FB asym., etc) in UA1-UA5 experiments.

– 2002-2005 : retuning parameters in Tune A and making a set of new tunes, AW, BW, DW, DWT, QW (R.Field & Co): “Old UE”

– 2004-today: tunes S0-S2, ..., Perugia (P.Skands &Co.): “new UE”
  http://theory.fnal.gov/trtles/ : latest Fermilab UE workshop
  http://www.pg.infn.it/mpi08/ : Perugia workshop
  – Pythia 8: implementation of various DP scattering combinations.

PHOTON AND JET EFFICIENCIES

The difference in DI and DP efficiencies can be caused by different amount of underlying energy in the single and double ppbar collision events. As a result, one can expect different photon selection, jet reco and jet finding efficiencies as well as jet energy scale.

The jet efficiencies are calculated using MIXDP and MIXDI "γ+3jets" signal samples built in data. The ratios of DI/DP efficiencies are found to be 0.93 ± 0.04. Systematics is relative 5.5%.

Photon efficiencies have been calculated in 'γ+≥3 jets' MC events with 1 and 2 vertices. Found ratio for 1VTX/2VTX events is 0.97 ± 0.02.

Agreement of photon purities has been checked separately using di-jet QCD 1&2 VTX samples. The found ratio is 0.99 ± 0.06.

Fit method

- Minimize chi2 (used in many PDF fits, dijet angular PRL)

$$\chi^2(\xi, \vec{\epsilon}, \vec{\alpha}) = \sum_i \frac{\left[d_i - t_i(\xi, \vec{\alpha}) \left(1 + \sum_j \delta_{ij}(\epsilon_j)\right)\right]^2}{\sigma^2_{i,\mathrm{stat.}} + \sigma^2_{i,\mathrm{uncorr.}}} + \sum_j \epsilon_j^2 + \sum_k \alpha_k^2$$

→ 23 experimental correlated sources of uncertainty
→ non-perturbative corrections uncertainties
→ PDF uncertainties

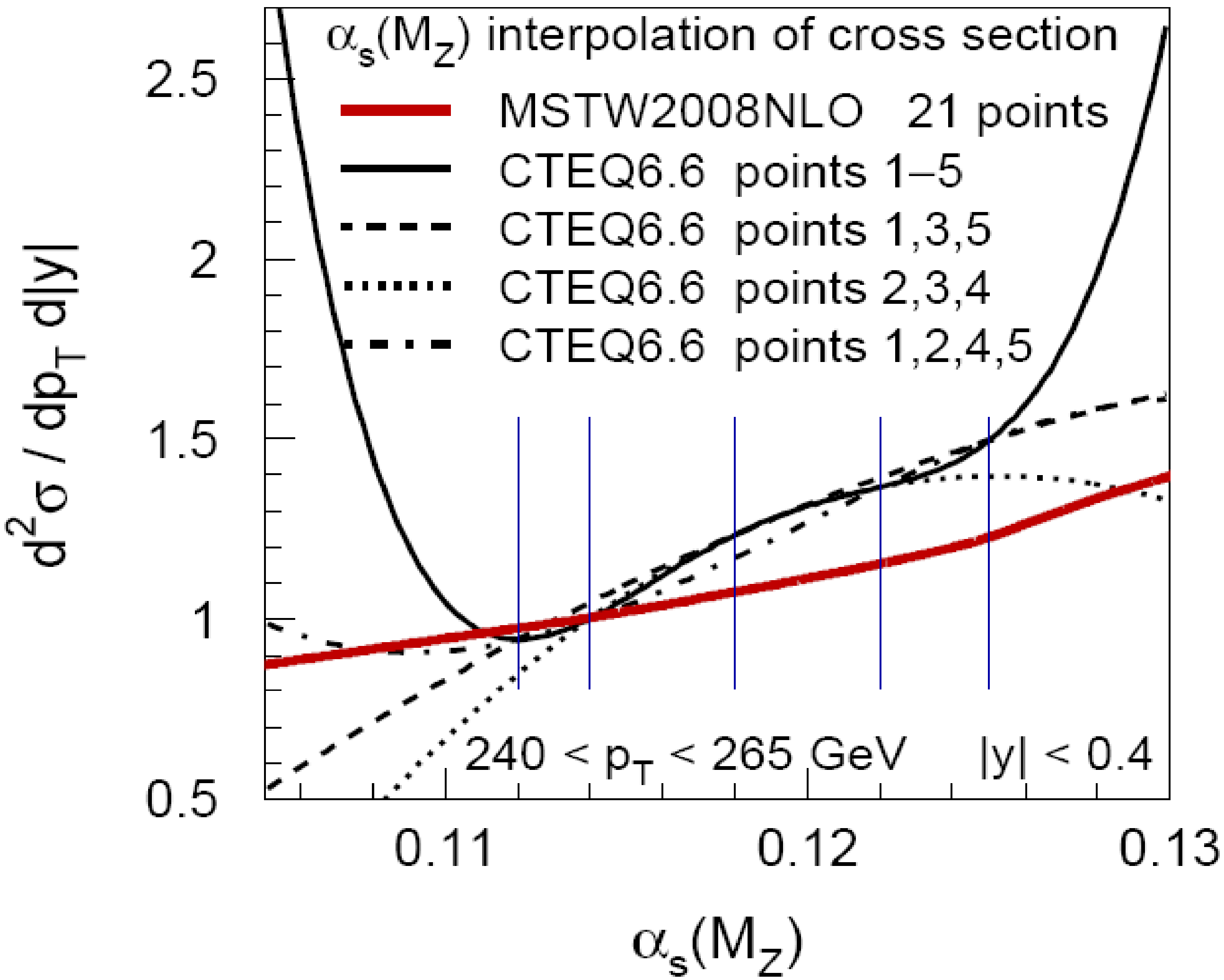
Separate treatment for **renormalization and factorization scales** (convention from LEP, HERA):

- perform fits for fixed scale
- repeat for scale factors 2.0, 0.5
- quote differences as 'scale uncertainty'

→ does not assume Gaussian distributed scale uncertainties

alphas dependence of PDFs

Compare cross section interpolations for MSTW2008 and CTEQ6.6



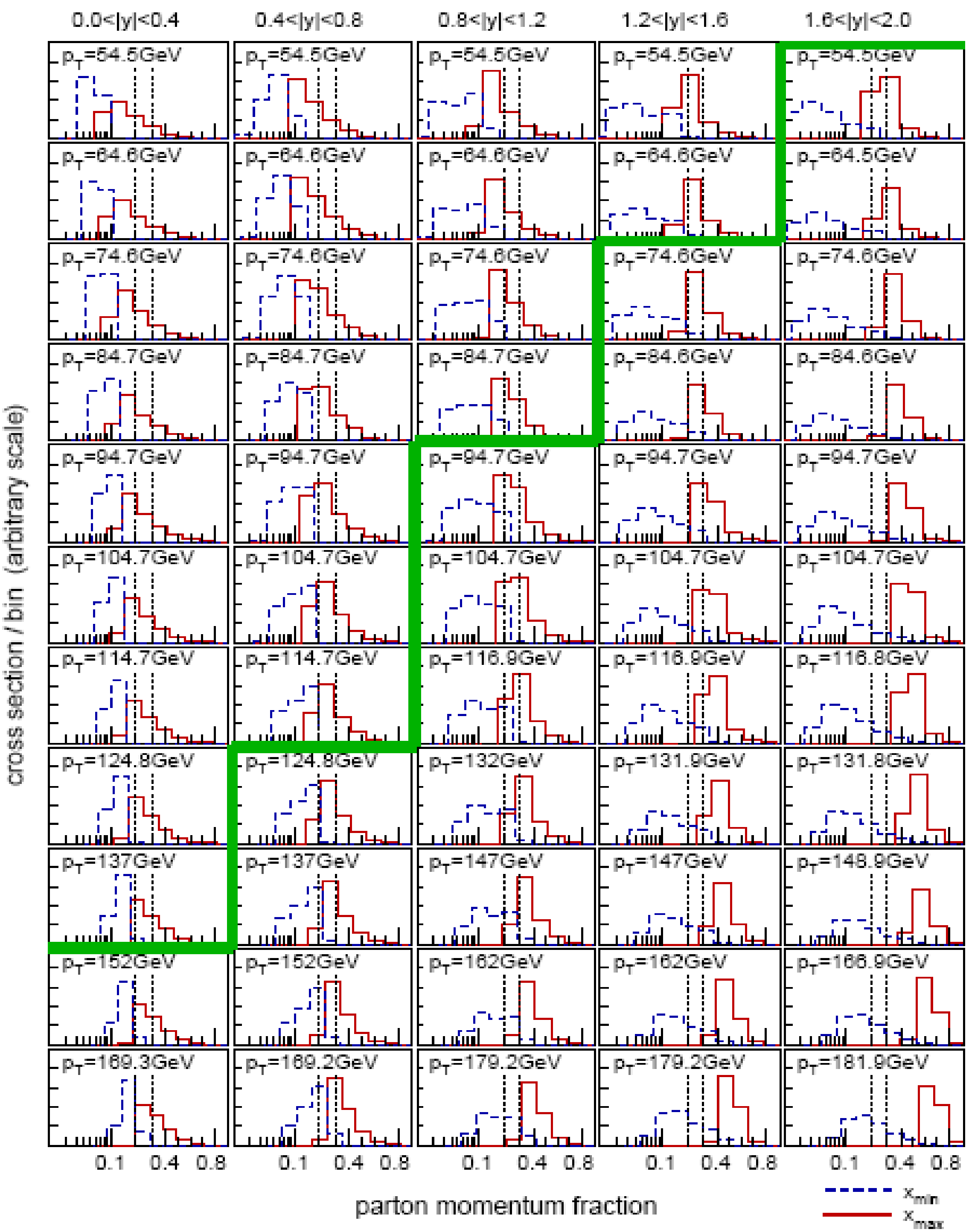
See:

For MSTW2008:
nice & smooth interpolation

CTEQ6.6:
Significant differences between different interpolations.
No obvious preference
(maybe points 1,3,5 because of monotonic behavior – but can't be justified)

→ Can not justify to use CTEQ6.6
→ But MSTW2008 is o.k. → provide NNLO

x-min / x-max distributions



Every analysis bin is one plot

Each plot: x-min & x-max distributions

x-min/max = min/max (x1, x2)

- What is the x-value for a given incl. jet data point @(pT, |y|) ?

→ Construct 'test-variable' (treat as if other jet was at y=0):

x-test = xT[exp(|y|) +1] / 2

- Cut on test-variable x-test < 0.15

→22 data points remain

→ It corresponds to data points with x-max peaking at x-max<0.2

→The data points have small contributions from x>0.2-0.3

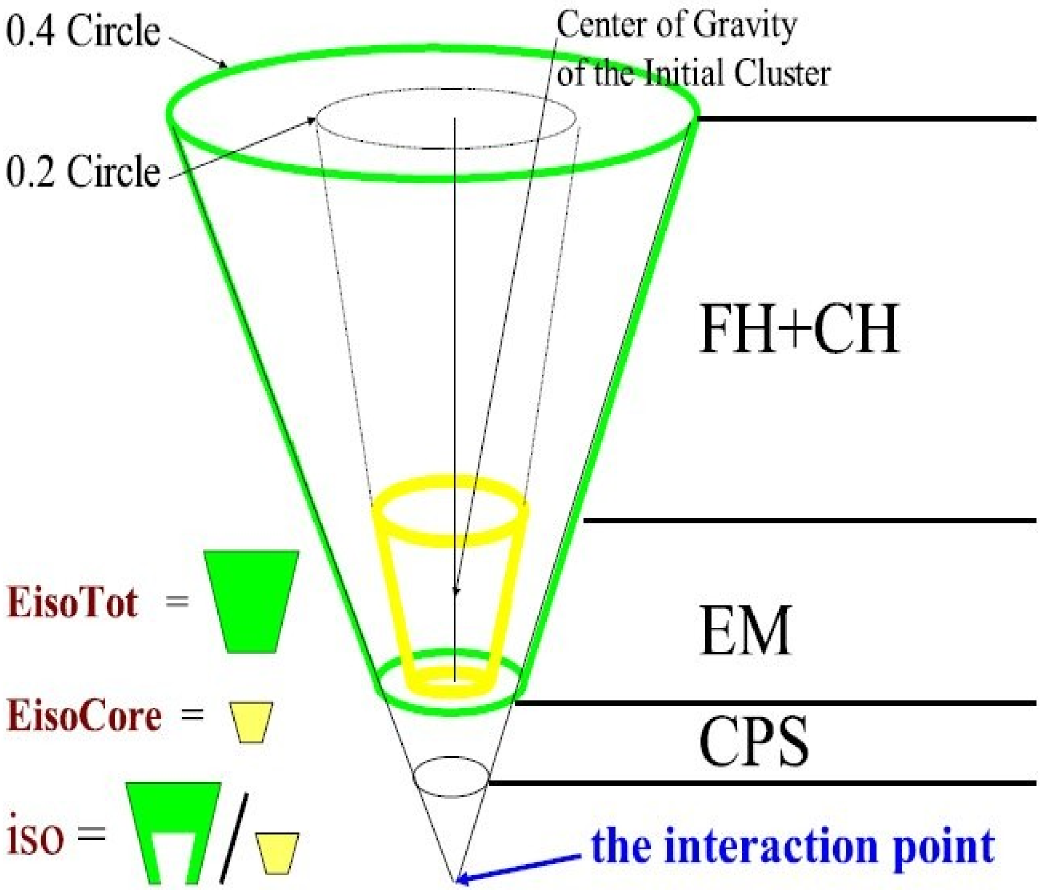
← Only data points above green line are used

x-test dependence

→ Consistent with assumption that for x-test<0.15 where the Tevatron jet data are not the dominant source of PDF information

- another test: redefine x-test with $y_2 = \pm|y|$
  → Result are consistent within 1%

Photon Identification



- EM shower in calorimeter candidate
- No associated track
- Isolation criteria

$$\text{Define } R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$$

$$Isol = \frac{E_{\text{tot}}(R{=}0.4) - E_{\text{EM}}(R{=}0.2)}{E_{\text{EM}}(R{=}0.2)} < 0.07$$

- EM fraction > 96%
- Photon ANN Output > 0.5
  (based on Calo, CPS and track information)
- dR$(\gamma,$ jet$)$ > 0.7

Fermilab Tevatron Run II

$\sqrt{s}$ = 1.96 TeV
Peak Luminosity: 3.5x10^{32} $cm^{-2}s^{-1}$
About 6.7 fb^{-1} delivered
Experiments typically collect data with 80-90% efficiency