Investigation of
Double-Parton Scattering (DPS)
at the LHC
Focusing on
3Jet+Gamma Topologies

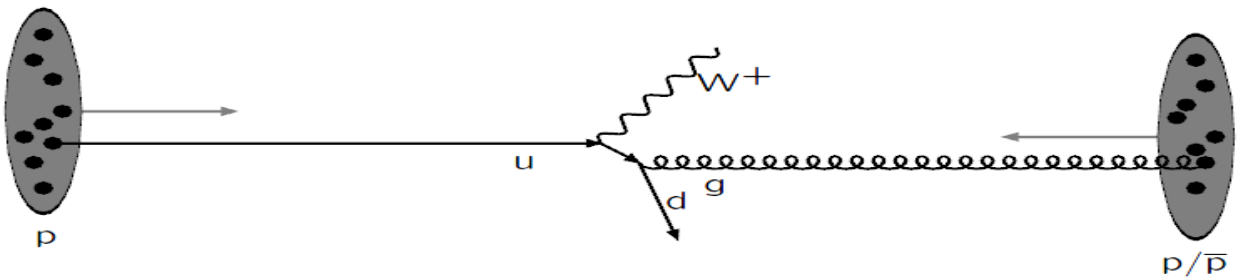
(With emphasis on Monte Carlo simulations)

Connected to CMS – QCD 10 - 039

Hugh Tay

Supervisor: Paolo Bartalini

Introduction

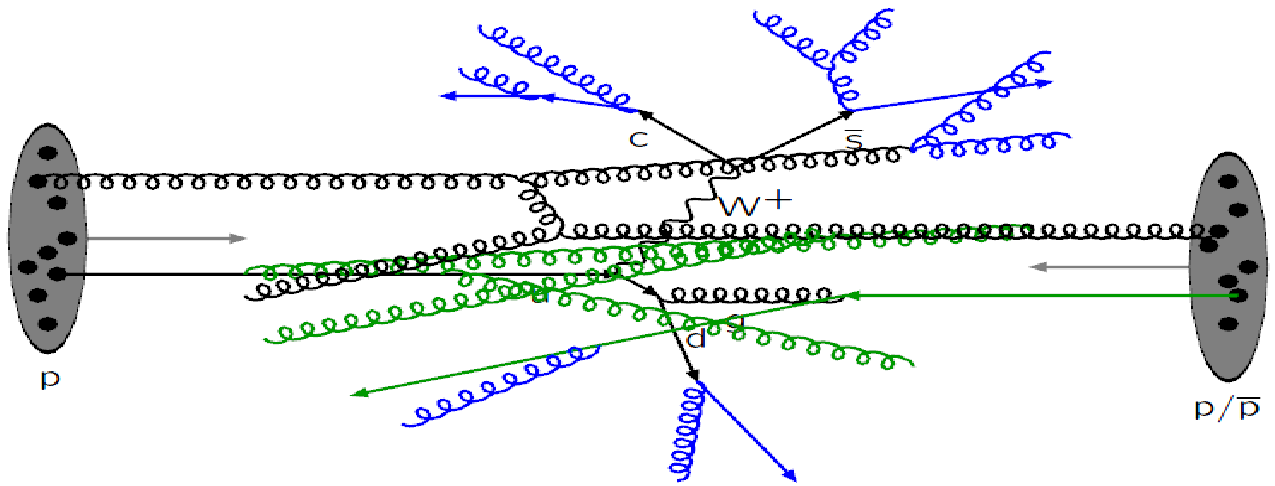


Lecture by Torbjörn Sjöstrand, April 2005

- Factorization theorem:
  2 protons collisions described in terms of ONE parton-parton (hard) scattering

- However, observations (AFS, CDF, D0) indicate that things are more complicated…

Introduction



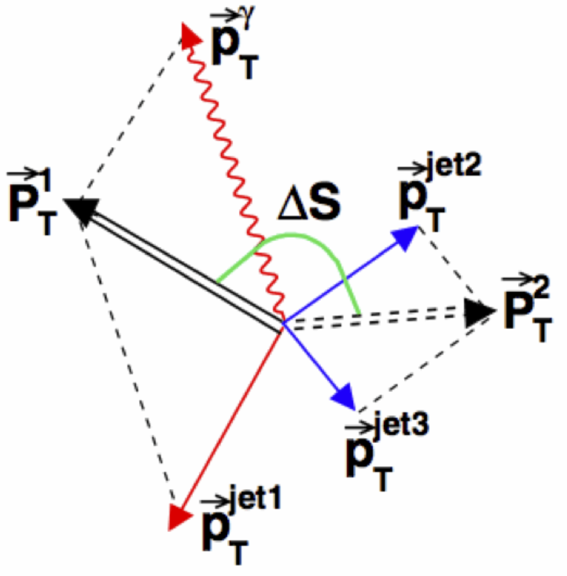
Lecture by Torbjörn Sjöstrand, April 2005

- Multiple-Parton Interactions!
  - Usually soft; contribute to Underlying Event

  - Sometimes hard;
    Can give rise to additional hard interactions!

Introduction

- Instead of using 4-jet events to study DPS,
  We concentrate on the “cleaner” 3jet+γ final state:



- Define *Gamma-Jet* as Process A, *Di-Jet* as Process B
  - **Theory predicts ~ process/scale independency of correlations**
    [Treleani et al.; rich bibliography]

Introduction

- Cross-section for getting both processes together:

$$\sigma_{AB} = (\sigma_A \sigma_B) / \sigma_{effective}$$

- In terms of Probabilities:

$$P(B \mid A) = \sigma_B / \sigma_{effective}$$

- Trivial case : $\boldsymbol{\sigma_{effective}} = \boldsymbol{\sigma_{inelastic}}$ – when **no** correlations.

Monte Carlo Simulation - PYTHIA

- PYTHIA 6, 8 – What they are & what they do:

  - General-purpose Monte Carlo Simulations for HEP
  - Random; Stochastic implementation of QM
  - Can be used by both theorists & experimentalists
  - Parton showers, underlying event, min. bias, MPI’s, etc.
  - Additional plug-ins (HepMC, PDF, SUSY, Higgs, etc.)
  - Adequate for generating multiparticle events

  - In PYTHIA 8, we can force Double-Parton Scattering

The Project

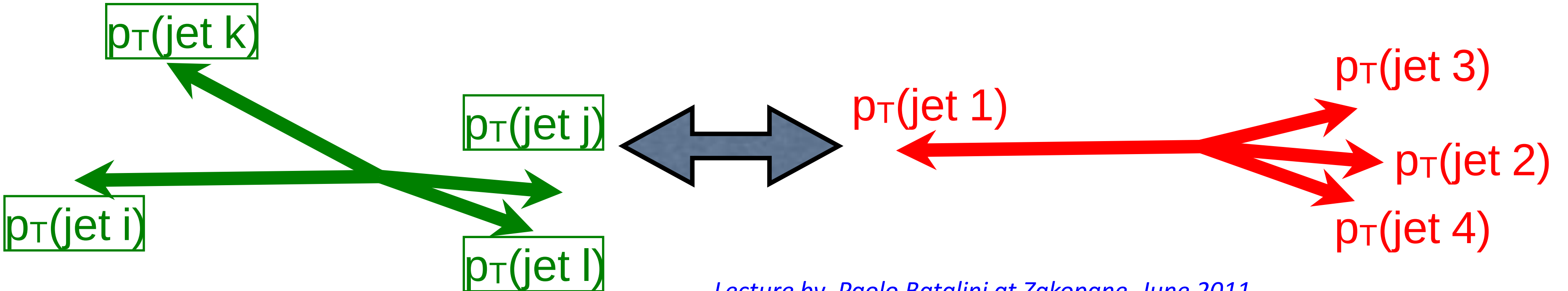
- Extracting $\sigma_{effective}$ at different working points (scales) for various tunes to test PYTHIA performance in handling MPI's

- Cross-check against CDF data; LHC data still being analyzed

- Necessary to know PYTHIA features in the DPS simulation Also useful in defining the backgrounds of new physics.

The Project

Need to *distinguish* double-parton-scattering from bremsstrahlung!



Lecture by Paolo Batalini at Zakopane, June 2011

- Easiest way – look at the jet $\boldsymbol{p_T}$'s
- Additional MPIs at the 2-3 GeV/c scale → UE
- We want the MPI's giving rise to a clear jet structure
- Hence set minimum $\boldsymbol{p_T}$ cut-off

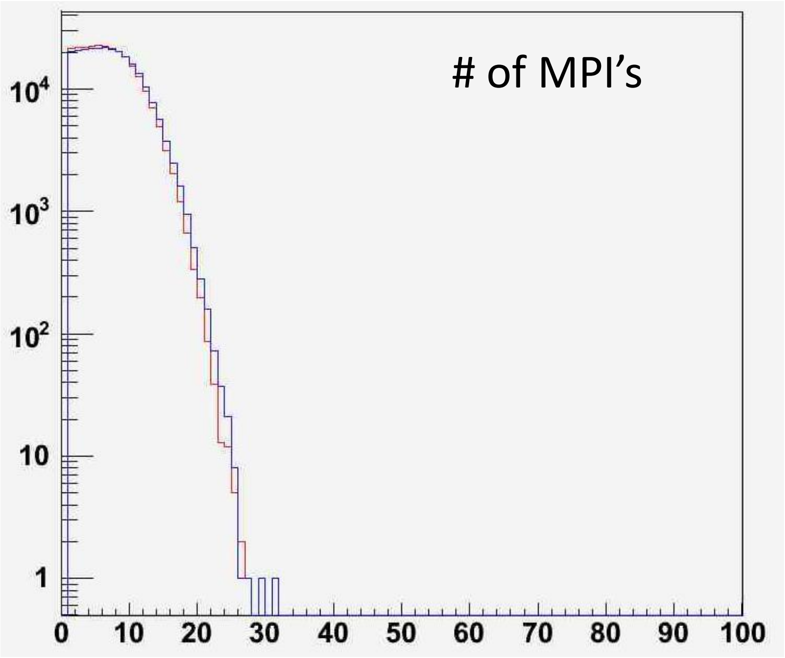
The Project

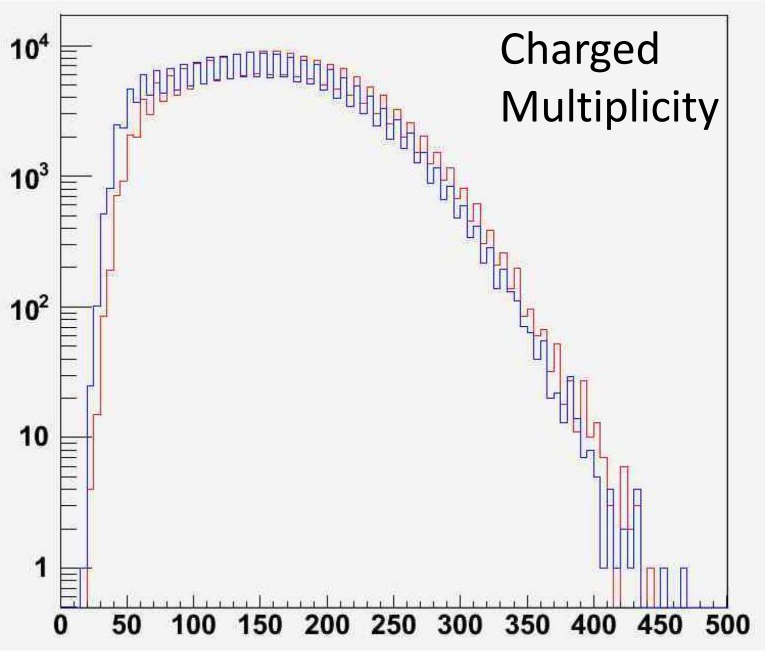
- Pythia 8 – 2C, 4C tunes;
  Pythia 6 – CW, DW, D6T tunes (in CMSSW framework)

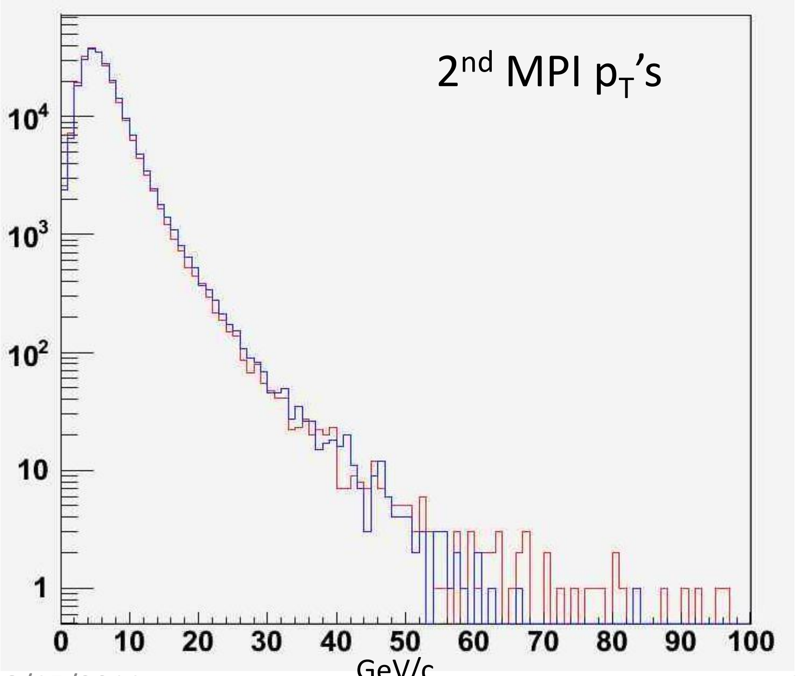
- Set Process A (Gamma-Jet) as the leading jet with minimum p_T of 20, 50, 100, 200 GeV/c

- Look for Process B (di-Jet) events with p_T cut-offs of 5, 10, 20, 50 GeV/c

- So we have 16 working points altogether





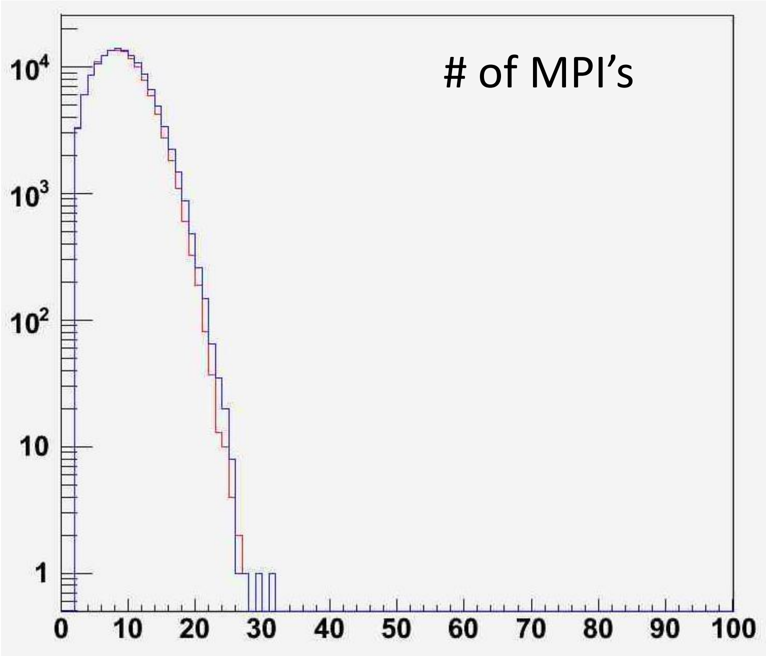


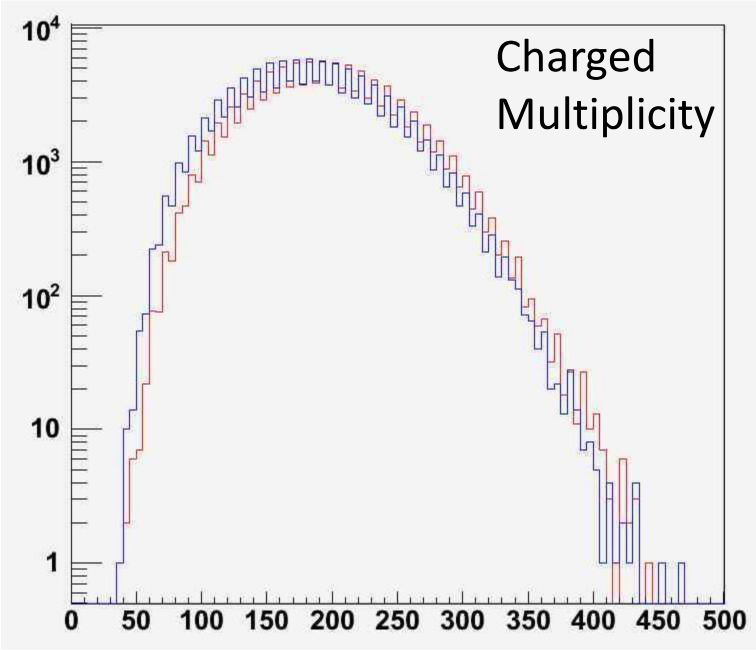
LHC – 7 TeV

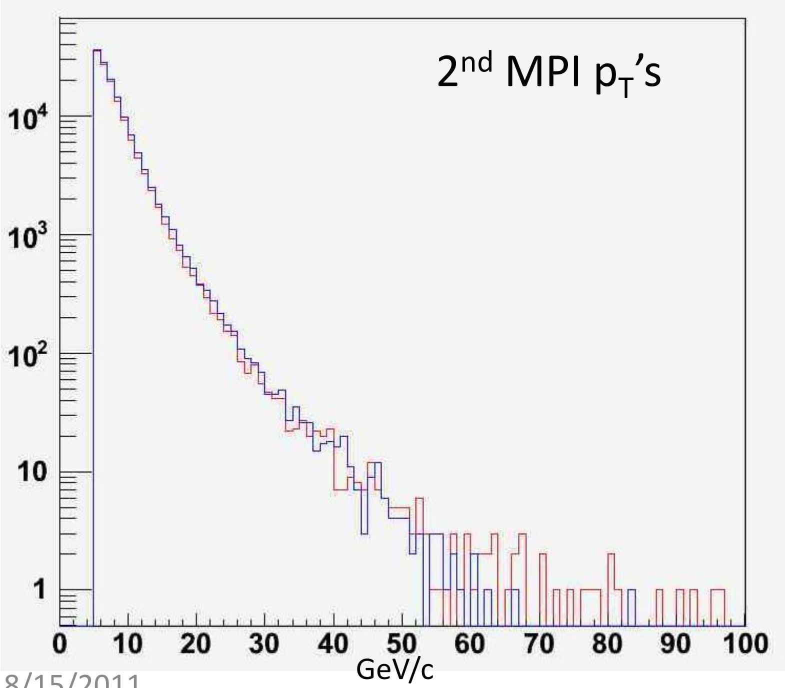
Plots for A=50 and 200 GeV/c
Showing overall statistics

Red – A=200 GeV
Blue – A=50 GeV

Process A – Gamma Jet
Process B – Di-jet





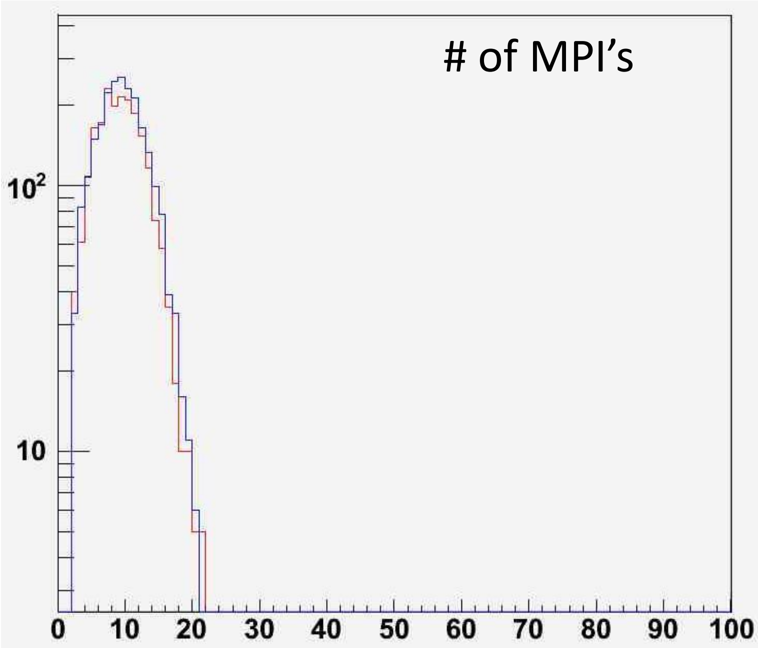


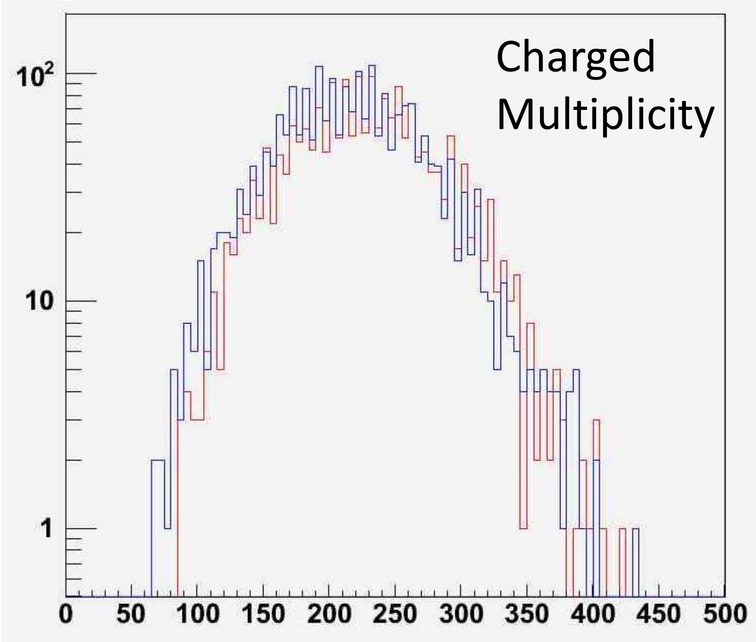
LHC – 7 TeV

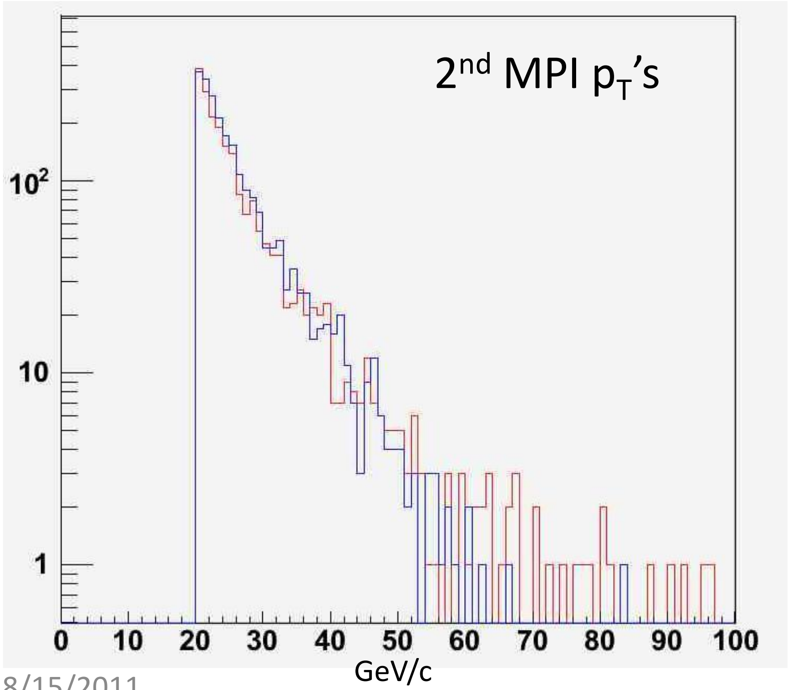
Plots for A=200,50
Showing statistics for **B>5**

Red – A=200
Blue – A=50

Process A – Gamma Jet
Process B – Di-jet







LHC – 7 TeV

Plots for A=50,200
Showing statistics for **B>20**

Red – A=200
Blue – A=50

Process A – Gamma Jet
Process B – Di-jet

Tevatron @ Pythia 8, 4C Tune

- Gamma-Jet (Process A) cross-section @ 50 GeV/c
  - 4C Tune : 421.7 ± 2.275 pb

- Di-Jet (Process B) cross-section @ 20 GeV/c
  - 4C Tune : 37.90 ± 0.062 μb

NOTE: LO cross-section as predicted by Pythia-8, no K factors applied!

Tevatron @ Pythia 8, 4C Tune

- Free (Inclusive, units - mb)

$\sigma_{eff}(A_n+B_m)$	*B>5*	*B>10*	*B>20*	*B>50*
A=20	4.81E+01	3.59E+01	6.71E+01	**#DIV/0!**
A=50	5.01E+01	3.90E+01	3.58E+01	7.25E+01
A=100	5.34E+01	4.18E+01	4.45E+01	4.23E+01
A=200	6.26E+01	5.40E+01	6.02E+01	8.46E+01

- Forced (Exclusive, units - mb)

$\sigma_{eff}(A_n+B_m)$	*B=5*	*B=10*	*B=20*	*B=50*
A=20	2.96E+01	3.08E+01	3.19E+01	3.44E+01
A=50	3.08E+01	3.24E+01	3.44E+01	3.93E+01
A=100	3.20E+01	3.44E+01	3.94E+01	4.80E+01
A=200	3.63E+01	4.13E+01	5.00E+01	7.46E+01

LHC – Pythia 8, 2C and 4C Tunes

- Gamma-Jet (Process A) cross-section @ 50 GeV/c
  - 2C Tune : 3.504 ± 0.018 nb
  - 4C Tune : 3.535 ± 0.018 nb

- Di-Jet (Process B) cross-section @ 20 GeV/c
  - 2C Tune : 344.6 ± 0.586 μb
  - 4C Tune : 344.1 ± 0.584 μb

NOTE: LO cross-section as predicted by Pythia-8, no K factors applied!

LHC @ Pythia 8, 2C Tune

- Free (Inclusive, units - mb)

$\sigma_{eff}(A_n+B_m)$	*B>5*	*B>10*	*B>20*	*B>50*
A=20	7.97E+01	3.91E+01	6.03E+01	**1.83E+03**
A=50	8.05E+01	3.86E+01	3.42E+01	6.66E+01
A=100	8.20E+01	3.99E+01	3.54E+01	2.99E+01
A=200	8.38E+01	4.19E+01	3.66E+01	3.62E+01

- Forced (Exclusive, units - mb)

$\sigma_{eff}(A_n+B_m)$	*B=5*	*B=10*	*B=20*	*B=50*
A=20	3.14E+01	3.12E+01	3.19E+01	3.28E+01
A=50	3.14E+01	3.22E+01	3.27E+01	3.41E+01
A=100	3.27E+01	3.30E+01	3.39E+01	3.52E+01
A=200	3.30E+01	3.38E+01	3.59E+01	3.77E+01

LHC @ Pythia 8, 4C Tune

- Free (Inclusive, units - mb)

$\sigma_{eff}(A_n+B_m)$	*B>5*	*B>10*	*B>20*	*B>50*
A=20	7.81E+01	3.97E+01	6.27E+01	**1.03E+03**
A=50	7.88E+01	3.94E+01	3.43E+01	7.66E+01
A=100	8.05E+01	4.10E+01	3.66E+01	3.90E+01
A=200	8.23E+01	4.32E+01	3.79E+01	3.57E+01

- Forced (Exclusive, units - mb)

$\sigma_{eff}(A_n+B_m)$	*B=5*	*B=10*	*B=20*	*B=50*
A=20	3.37E+01	3.31E+01	3.41E+01	3.46E+01
A=50	3.41E+01	3.50E+01	3.50E+01	3.59E+01
A=100	3.48E+01	3.55E+01	3.58E+01	3.83E+01
A=200	3.49E+01	3.63E+01	3.74E+01	4.04E+01

LHC @ Pythia 8, 4C Tune

- Free - Forced % Difference

$\sigma_{eff}(A_n+B_m)$	*B>5*	*B>10*	*B>20*	*B>50*
A=20	132.2	19.8	83.6	**2888.1**
A=50	130.9	12.3	-1.8	113.7
A=100	131.5	15.6	2.1	2.0
A=200	135.9	19.1	1.2	-11.7

Much more Interesting for DPS studies!

Soft – relevant for UE

- (Free) 4C - 2C % Difference

$\sigma_{eff}(A_n+B_m)$	*B=5*	*B=10*	*B=20*	*B=50*
A=20	1.9	-1.6	-3.9	77.3
A=50	2.2	-1.9	-0.4	-13.1
A=100	1.8	-2.8	-3.1	-23.4
A=200	1.8	-3.0	-3.6	1.5

Issues with DPS Generation

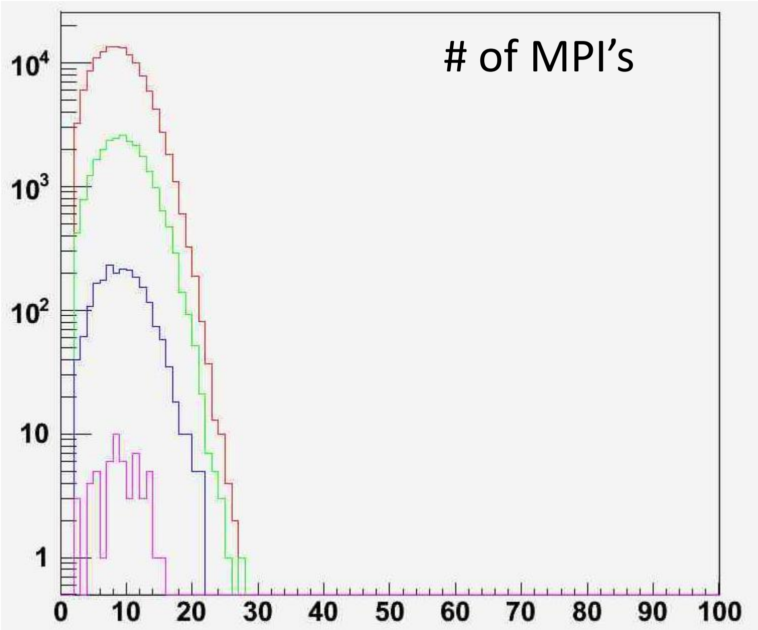
(When Process B is Free/Inclusive)

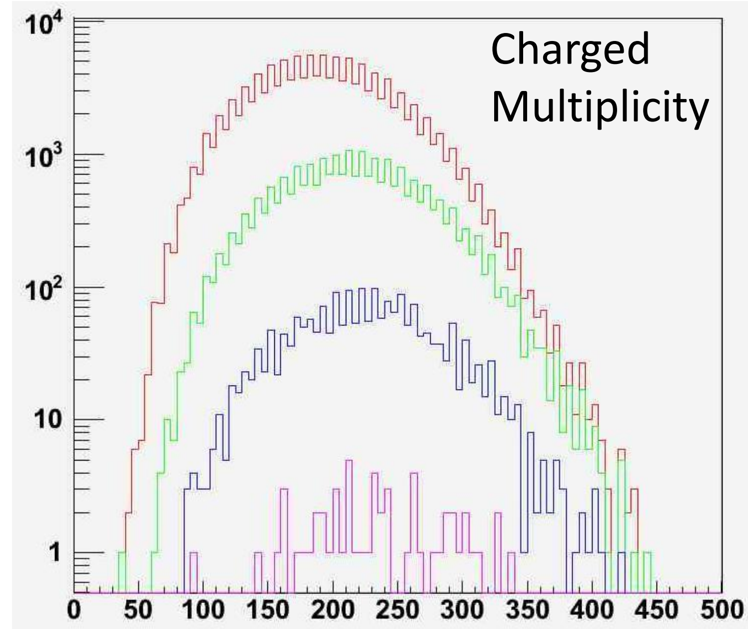
- Limitation of PYTHIA
  For the processes included in the MPI's, the $\boldsymbol{p_T}$'s are generated in decreasing order.

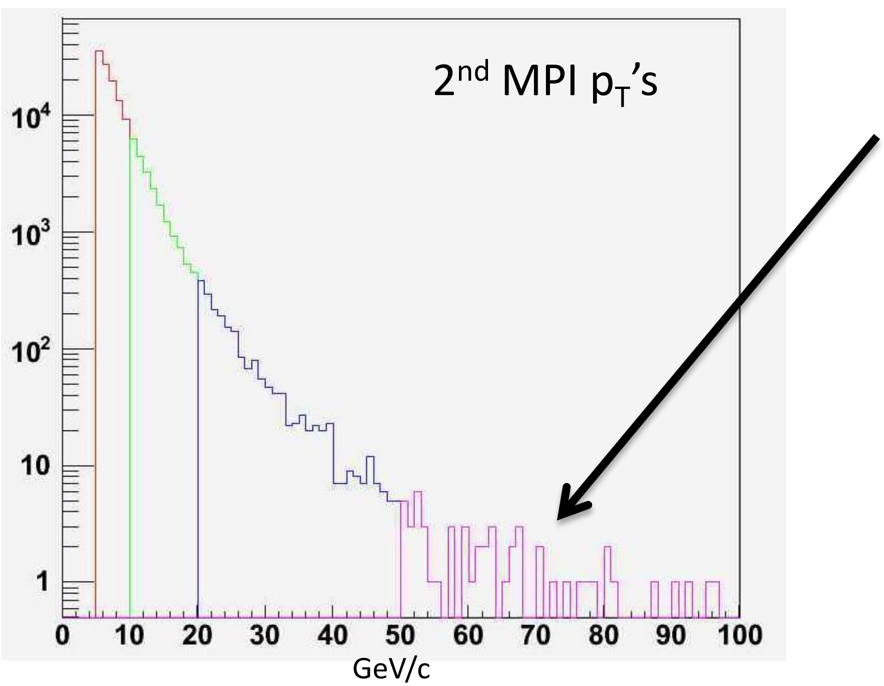
- Secondary processes cannot exceed leading processes.

  → For B>50, A *must* >50 as well

  ∴ Poor statistics for [A=20, B>50], and $\boldsymbol{\sigma}_{effective}$ is overestimated by 1-2 orders of magnitude!







LHC – 7 TeV

Plots for A=200
Showing statistics for all B's

Red	–	B>5
Green	–	B>10
Blue	–	B>20
Purple	–	B>50

Finding the 'missing' DPS Events

- Invert the process : Now take B (di-Jet) as leading process and look for A processes (Gamma-Jet) in the MPI's

- Effective Cross-Sections for [A=20, B=50]
  -> With B Leading : **27.6** ± 15.9 mb ✓

- In general, one should find the **HARMONIC MEAN** of $\sigma_{effective}$ for A and B set as the leading process, *in turn*.

→ **NOTE: DO THE MASSIVE PRODUCTIONS FOLLOW THIS RULE?**

LHC @ Pythia 8 4C Tune

- Corrected table for free (inclusive) production; units - mb

$\sigma_{eff}(A_n+B_m)$	*B>5*	*B>10*	*B>20*	*B>50*
A=20	7.81E+01	3.97E+01	1.92E+01	**2.69E+01**
A=50	7.88E+01	3.94E+01	3.43E+01	**7.66E+01**
A=100	8.05E+01	4.10E+01	3.66E+01	3.90E+01
A=200	8.23E+01	4.32E+01	3.79E+01	3.57E+01

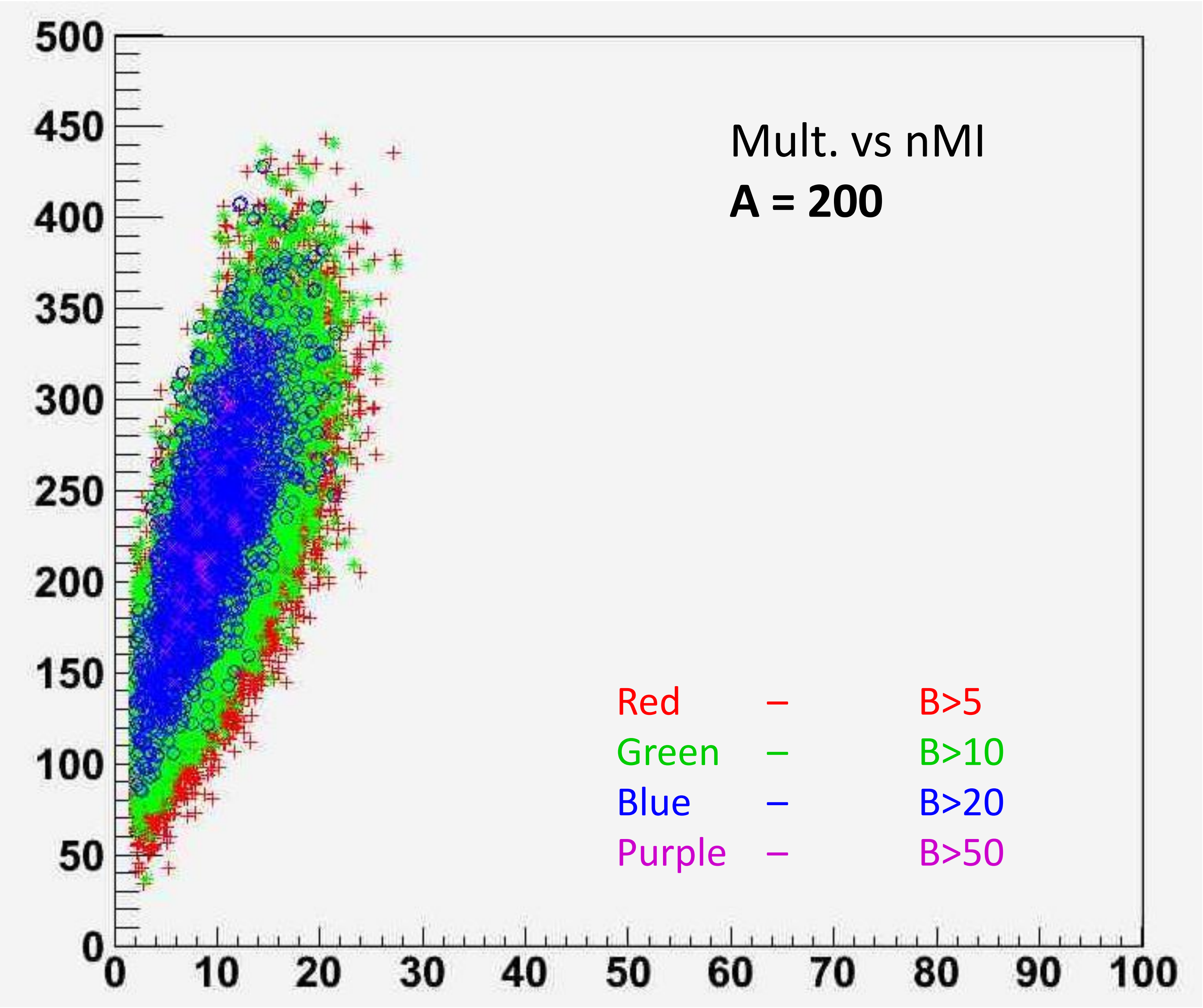
Comparison with Experiment

- **HOWEVER!**
  Measured $\sigma_{effective} \approx 11$ mb (3jet+γ by **CDF**, corrected by Treleani)
  [PRD76:076006,2007]
  - Means a factor of 3 lower than the Pythia 8 “predictions”!!!

- PYTHIA might be underestimating DPS in MPI’s even at **LHC**!

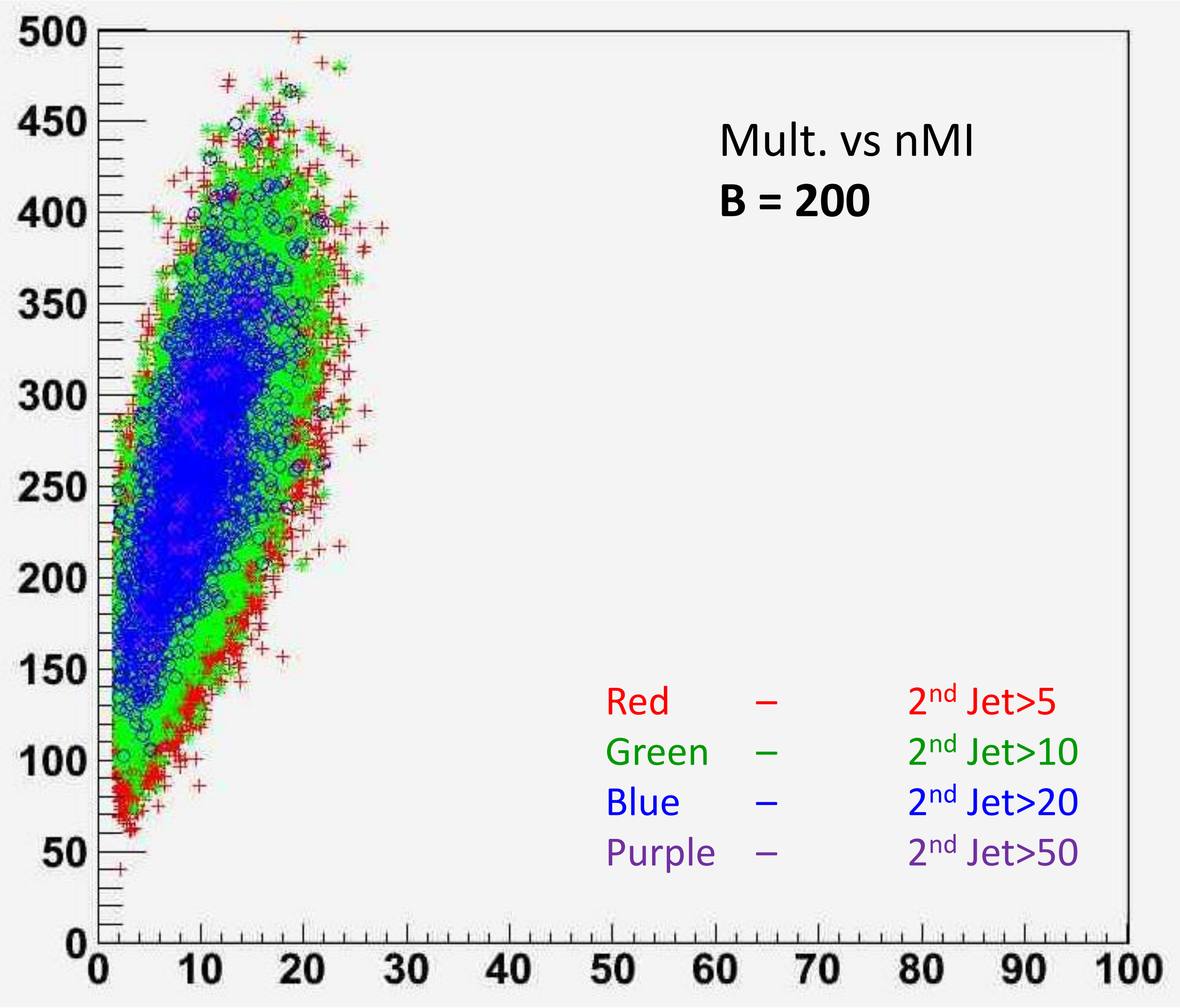
- So we still need to wait for CMS/ATLAS to measure the this effective cross-section at 7 TeV…

LHC – 7 TeV



Mult. vs nMI
A = 200
Red – B>5
Green – B>10
Blue – B>20
Purple – B>50
0
50
100
150
200
250
300
350
400
450
500
0
10
20
30
40
50
60
70
80
90
100

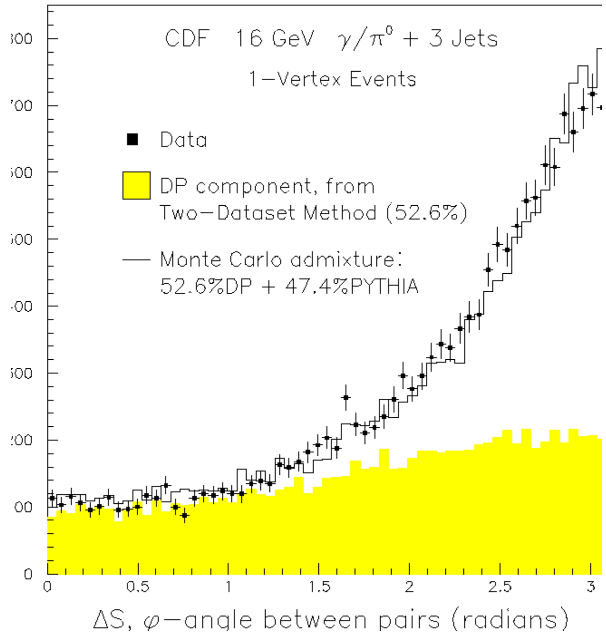
LHC – 7 TeV



Mult. vs nMI
B = 200
Red – 2nd Jet>5
Green – 2nd Jet>10
Blue – 2nd Jet>20
Purple – 2nd Jet>50
0
50
100
150
200
250
300
350
400
450
500
0
10
20
30
40
50
60
70
80
90
100

Future Work

- Studying the signal vs. background for 3jet+γ final state.



[CDF Collab., Phys. Rev. Lett. 79, 584 (1997)]

- Background defined by the setting the second interaction to have a $\boldsymbol{p^{\wedge}_T}$ below a given threshold

Future Work

- More statistics for critical working points (inclusive samples)
- Repeat exercise for A = t-tbar and W processes

THANK YOU!

Backup Slides

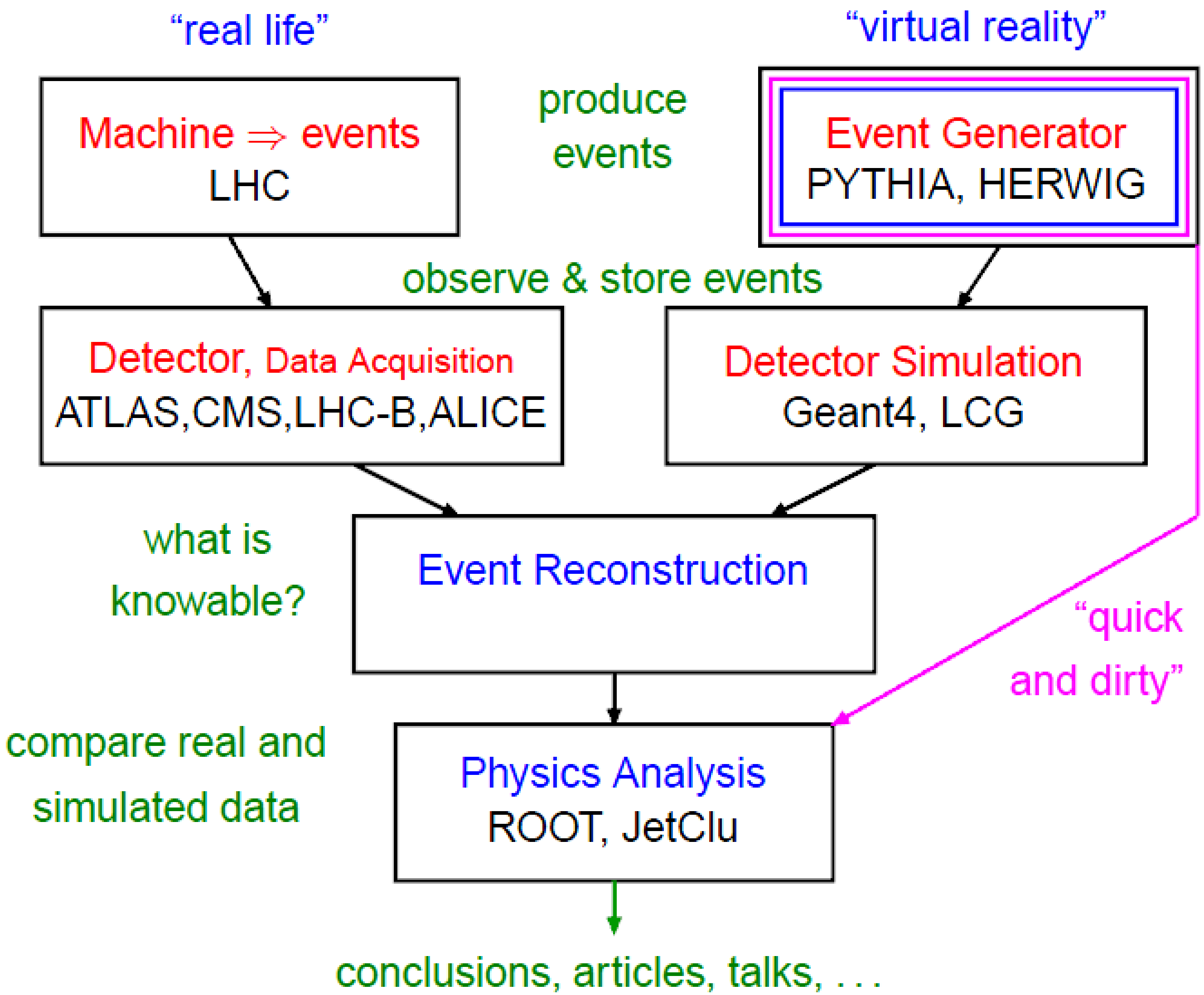
CMSSW Framework

- Analyzed 7 TeV events using Pythia 6 tunes
  - CW, DW, D6T database samples
  - (Z1, Z2 samples had technical glitch)

- Compared with Standalone PYTHIA (% Differences)

- Cross-checked with CDF data (LHC data coming soon)

Event Generator Flowchart



Lecture by Torbjörn Sjöstrand at CERN, April 2005

Pythia Tunes in CMS

[Cf. Rick Field, this school]

- Pythia 6 Virtuality ordered showers, old MPIs
  - **CTEQ5L** pre-LHC Tune **DW(T)** and LHC (UE@0.9 TeV) Tune **CW(T)**
  - **CTEQ6LL** pre-LHC Tune **D6(T)**

  [arXiv:1003.4220]
  - Describe UE@Tevatron, describe other very important observables at Tevatron like p_T(heavy bosons) and Jet azimuthal decorrelation
- Pythia 6 new MPIs with interleaved p_T-ordered showers **(MORE RADIATION, LESS MPIs)**
  - **CTEQ5L** LHC Tune **Z1** uses Professor AMBT1 LEP fragm. & ATLAS Min Bias: **Updated Color Rec.**
  - **CTEQ6LL** LHC Tune **Z2** by hand from Z1: decreased p_T cut off

  [arXiv:1012.5104, arXiv:1010.3558v1]
- Pythia 8, brand new MPI model, inteleaved p_T-ordered showers
  - **CTEQ5L** pre-LHC **Tune 1** first Pythia 8 Tune proposed by Peter Skands
  - **CTEQ6LL** Tevatron **Tune 2C** describes the relevant Tevatron phenomenology
  - **CTEQ6LL** LHC **Tune 4C** describes ATLAS MB & UE (leading track)

  [arXiv:1011.1759]

$p_{T0}^{LHC} = p_{T0}^{Tevatron} (\sqrt{s}^{LHC} / \sqrt{s}^{Tevatron})^{\varepsilon}$ **Where ε = PARP(90) or MultipleInteractions:EcmPow**

T versions (for example D6T) 2C, 4C → small $\varepsilon \approx 0.16 - 0.21$ (CTEQ6LL)

Tune 1, DW, Z1, Z2, CW → large $\varepsilon \approx 0.24 - 0.30$ (CTEQ5L, guess in Z2 wrong?)

Still no coherent description of Tevatron and LHC (more info in backup slides)

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