Multiple Parton Interactions (MPI) and Double Parton Scattering (DPS) studies at CMS

DIS - Marseille, April 23 2013

Paolo Bartalini (NTU)

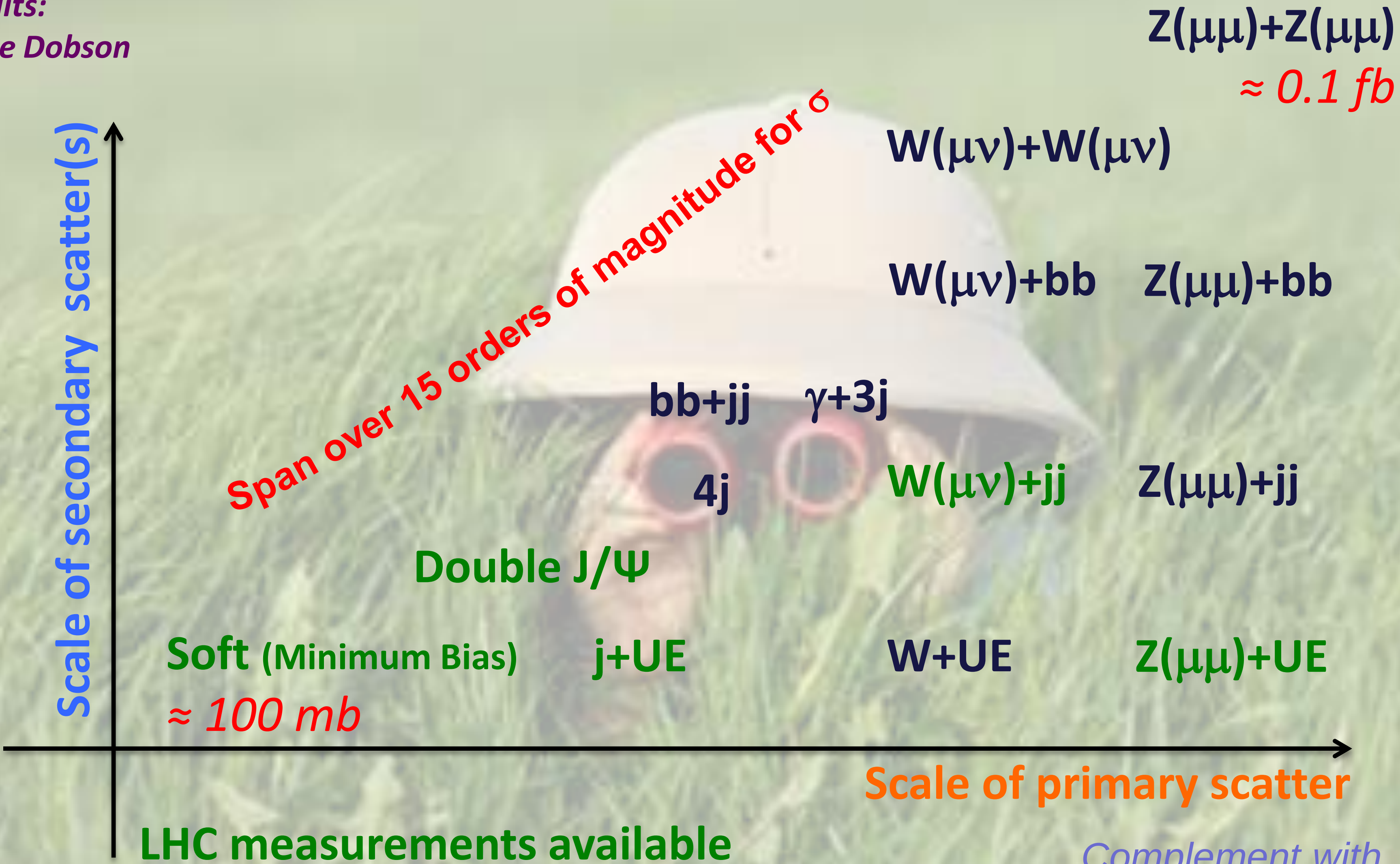
on behalf of the CMS collaboration

Emphasis on DPS (i.e. hard MPI)

[Wide spectrum of CMS - Soft QCD measurements concerned.
Here only few highlights are covered
The detailed list of CMS references Is reported in the back-up slides.]

Where can we see Multiple Parton Interactions?

Credits:
- Ellie Dobson



Z(μμ)+Z(μμ)
≈ 0.1 fb

W(μν)+W(μν)

Span over 15 orders of magnitude for σ

W(μν)+bb Z(μμ)+bb

bb+jj γ+3j

4j W(μν)+jj Z(μμ)+jj

Double J/Ψ

Soft (Minimum Bias) j+UE W+UE Z(μμ)+UE
≈ 100 mb

Scale of secondary scatter(s)

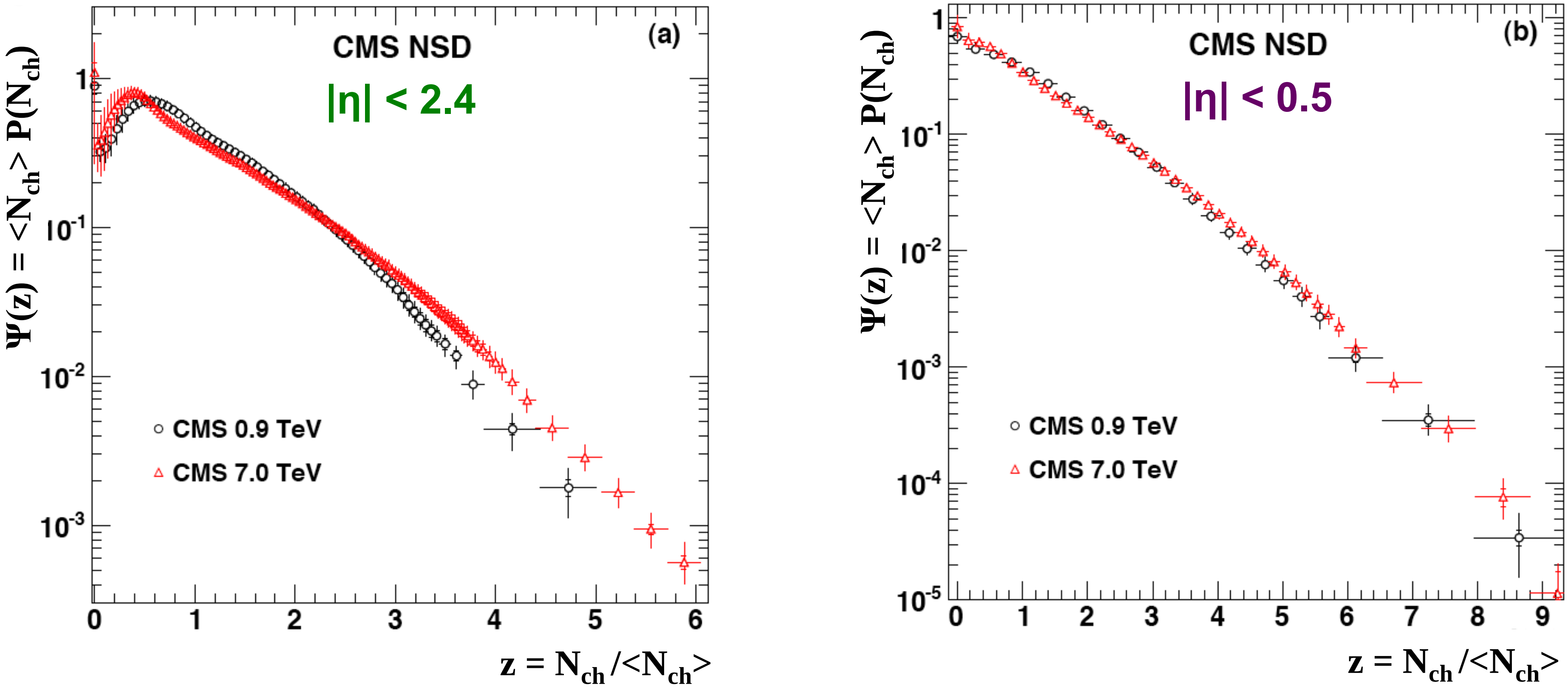
Scale of primary scatter

LHC measurements available

LHC measurements not yet available

Complement with
p-A and A-A

Violation of the KNO scaling



KNO Scaling [Koba, Nielsen, Olesen, Nucl. Rev. B40 (1972) 371].

Violation already reported by UA5 (and comparing ISR, SPS, Tevatron).

CMS confirms violation for |η|<2.4. Sensitive effect in the tails (large $z = N_{ch}/\langle N_{ch} \rangle$).

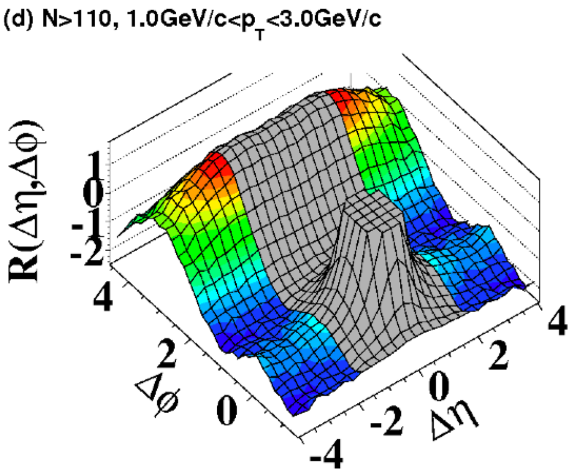
→ Interpretation: connected to the presence of Multiple Parton Interactions.

[QCD-10-004]

Associated 1D yields in bins of p_T and N_{ch}

Long range:

Project $2 < |\Delta\eta| < 4.8$ onto $\Delta\phi$:

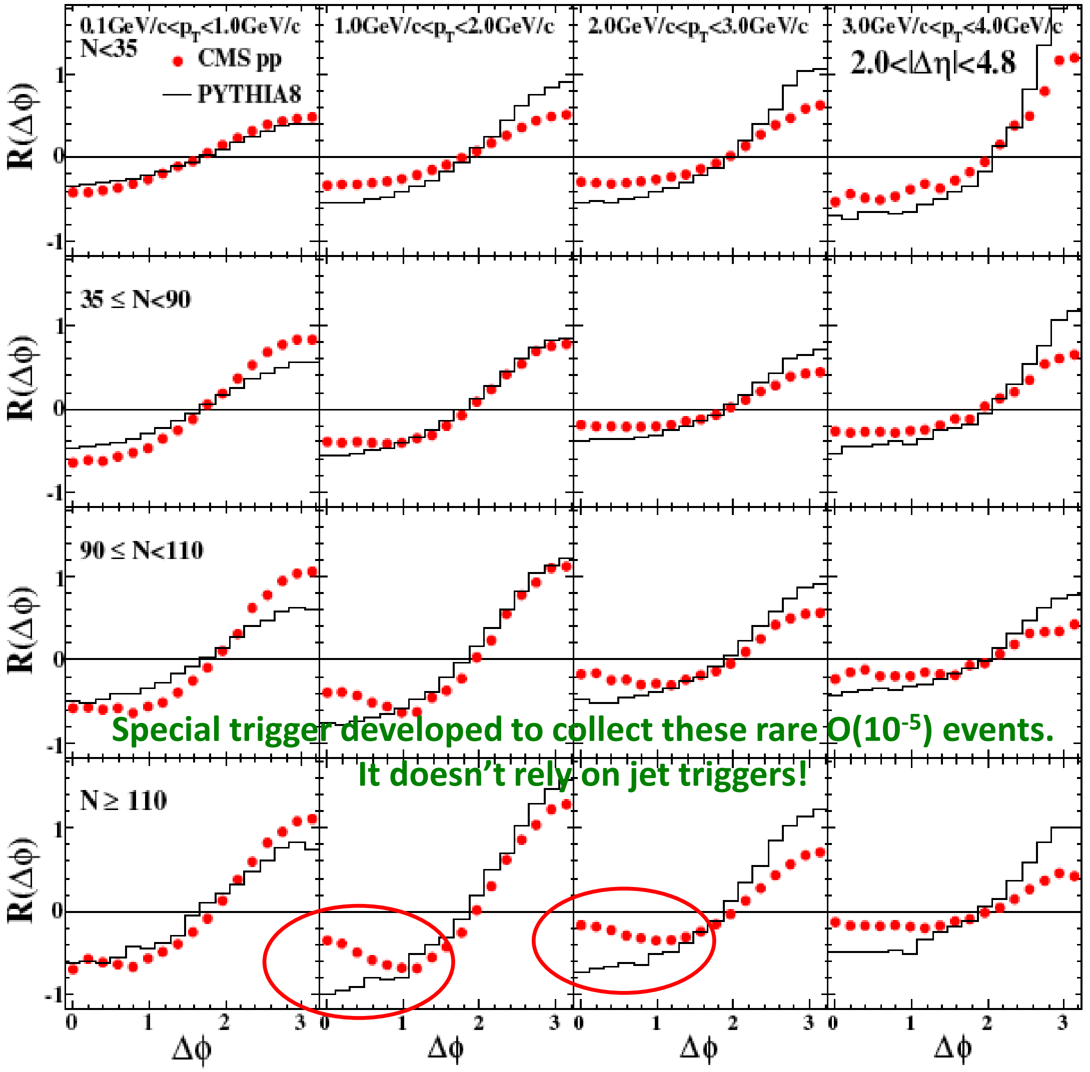

(d) N>110, 1.0GeV/c<p_T<3.0GeV/c

- **Ridge most pronounced for high multiplicity events and at $1 < p_T < 3$ GeV.**
- No ridge seen in tested MC models (Pythia 8, Pythia6, Herwig++, etc.)
- Several interpretations proposed for this HI-like effect in pp interactions.
- Clear major role of Multiple Parton Interactions.

[S. Alderweireldt, P.Mechelen arXiv:1203.2048]

Increasing p_T

Increasing multiplicity



Special trigger developed to collect these rare O(10^{-5}) events.

It doesn't rely on jet triggers!

UE activity in Jets and Drell-Yan Z(μμ) events

UE Measurements in (track) Jets:

Fast rise followed by plateau. Indication of two different regimes (two scale picture). MPI rise dominates at low p_T, radiation rise dominates at higher p_T.

→ UE in high p_T di-jet events is ≈ universal.

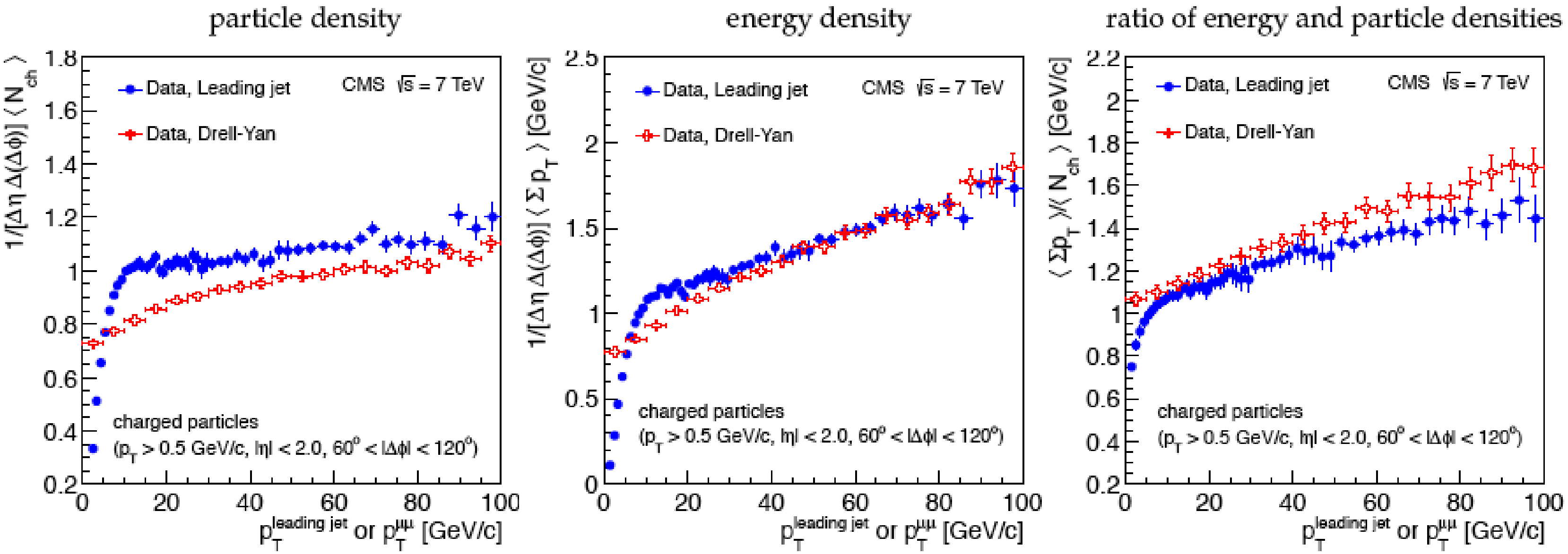
UE Measurements in Drell-Yan:

MPI saturated. Radiative increase of UE activity with p_T di-lepton.

Constant vs $M_{\text{di-lepton}}$.

→ Min activity around 80% with respect to the plateau in jet events.

81 GeV < $M_{\mu\mu}$ < 101 GeV



Transverse

[QCD-11-012]

Bottom line: the soft multiple parton intractions highlights

- Charged multiplicity measurements:
  - CMS confirms large multiplicity tails and KNO violation more pronounced at high energies.

  → On the other hand MPI models have been invented to describe large multiplicity tails and KNO violation at SPS.

- MPI certainly play a major role in the “ridge” effect at the LHC.

- UE Measurements
  - Single scale picture in the case of DY, two scale picture in the case of jets. See interpretation in the context of the GPDF (explaining also the relative size of UE(DY)/UE(jets).) → back-up slides.

- Evidence of MPI effects provided also in terms of Forward-Central correlations.

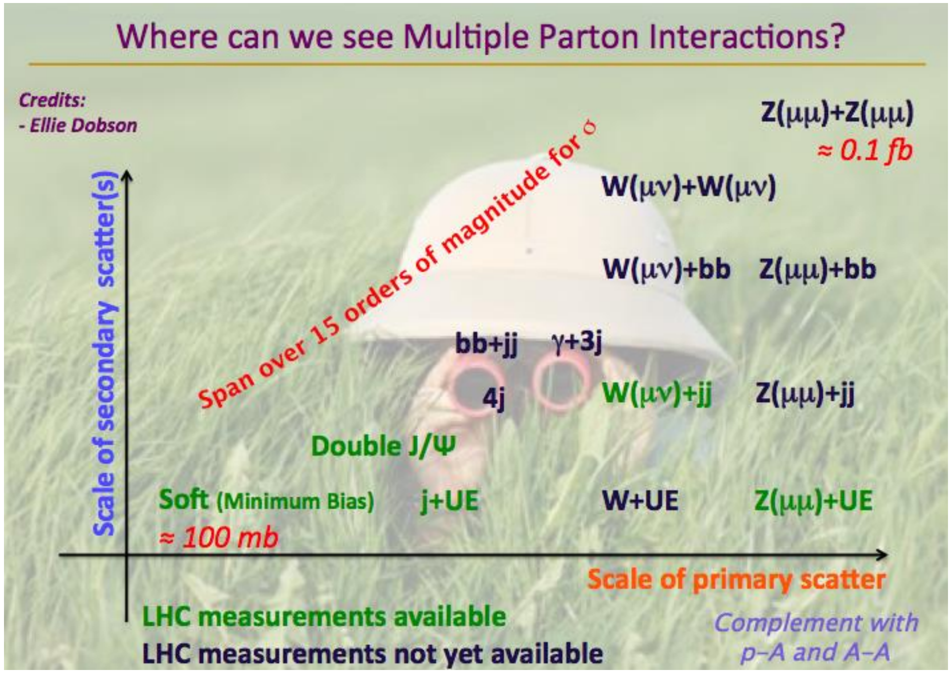
MPI from soft to hard: Double Parton Scattering

- $\sigma(A+B) = m * \sigma(A) * \sigma(B) / \sigma_{eff}$ (m = ½ for identical interactions, m = 1 otherwise)
  - $P(B|A) = P(B) * (\sigma_{Non\text{-}Diffractive}/\sigma_{eff})$
  - σ_{eff} mostly depends on geometry
  - $\sigma_{eff} \approx$ (process,) scale and √s independent according [D. Treleani et al., rich bibliography]
  - 3→4 processes give significant contributions, rising with $x_{Bjorken}$ [Y. Dokshitzer et al., this w/s]
- **Of course from an experimental point of view these possible properties should be tested!**

- $\sigma_{eff} \approx 10\div15$ mb from CDF & D0 3jet+γ, confirmed by ATLAS W+jets (talk @ DIS 2013) however LHCb reports discrepancies when comparing numbers from different channels: double J/ψ, J/ψ + open charm and double open charm prodution.
- Pythia: $\sigma_{eff} = \sigma_{Non\text{-}Diffractive} / \langle f_{impact} \rangle$ *[PLB707(2011) 52, …]*
  - where $\langle f_{impact} \rangle$ is tune dependent → σ_{eff} (Tevatron) ≈ 20÷30 mb

- **DPS underestimated in the models tuned on Soft QCD phenomenology?**
- **What are the relationships between "soft" and "hard" MPI measurements?**
- **Is the DPS experimental picture complete? Wich are the next steps/priorities?**
- **Which is the impact on new physics at the LHC/LIC?**

DPS milestones (a CMS view)



Where can we see Multiple Parton Interactions?

Credits:
- Ellie Dobson

Span over 15 orders of magnitude for σ

Scale of secondary scatter(s)

Scale of primary scatter

Z(μμ)+Z(μμ)
≈ 0.1 fb

W(μν)+W(μν)

W(μν)+bb Z(μμ)+bb

bb+jj γ+3j

4j W(μν)+jj Z(μμ)+jj

Double J/Ψ

Soft (Minimum Bias) j+UE W+UE Z(μμ)+UE
≈ 100 mb

LHC measurements available
LHC measurements not yet available

Complement with p–A and A–A

4. Differential distributions: require more data, HL-LHC, i.e. FUTURE…

3. Including more processes: study process dependency.

Forthcoming!

2. Interpretation, consistency check

Everybody (not only CMS) can take part in this game

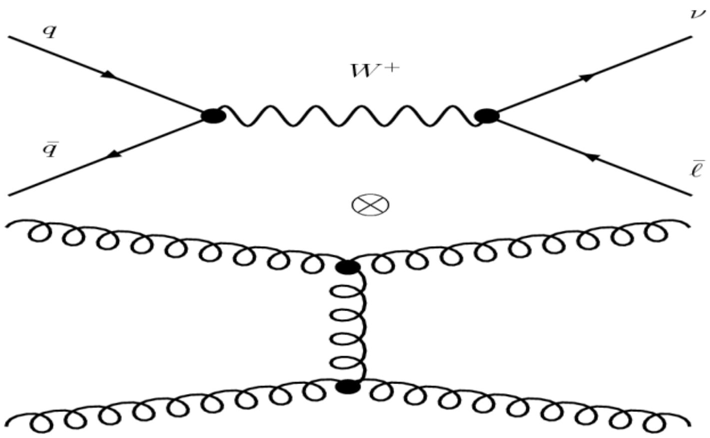
1. corrected distributions for several DPS-sensitive observables.

Achieved for W+2jets+X
(See next slides)

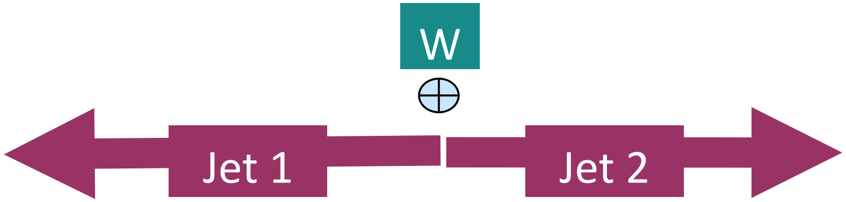
DPS via W + 2jets (+X) [CMS PAS FSQ-12-028]

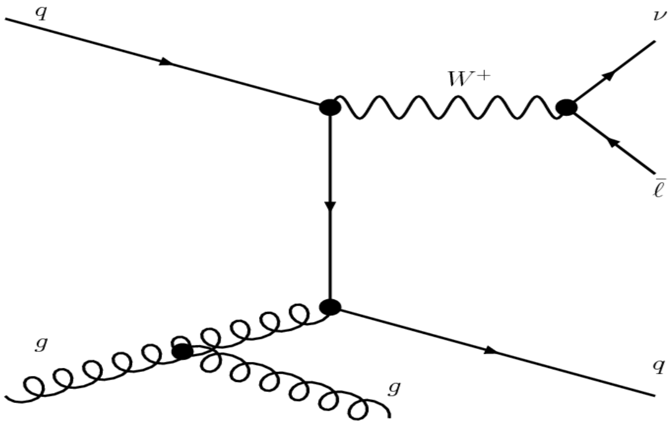
Signal: W from first hard parton-parton interaction, atleast two jets from second one.
Decay of W in “muon” channel is studied.

Background: W + jets from single interaction (SPS)



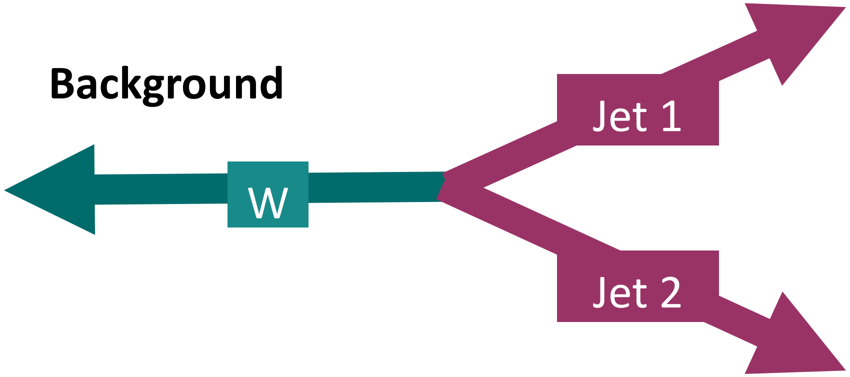
DPS, Signal





SPS, Background

Background



[FSQ-12-028]

Event Selection

Data:

- Full 2011 collision data at $\sqrt{s}$ = 7 TeV,
- Single Muon data streams with integrated luminosity of ~ 5 fb^{-1}

W selection:

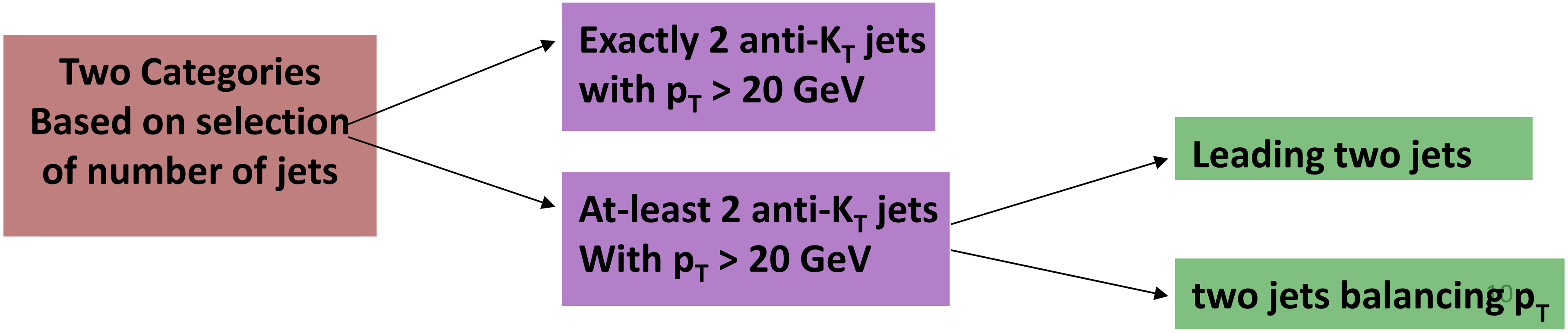
– Exactly one μ

– with p_T > 35 GeV, $|\eta| < 2.1$

– Required to be isolated and to pass tight ID criteria (details in CMS PAS FSQ-12-028)

– particle flow Missing Transverse Energy, MET (with type1 correction) > 30 GeV

– transverse mass of (μ and MET) > 50 GeV



Two Categories Based on selection of number of jets

Exactly 2 anti-K_T jets with p_T > 20 GeV

At-least 2 anti-K_T jets With p_T > 20 GeV

Leading two jets

two jets balancing p_T

Notice that the inclusive choice is the only one compatible with the σ_{eff} formalism

Observables in W → $l\nu$ + 2 jets + X analysis

Using different observables may bring to significant differences in σ_{eff} extraction (see for example the CMS-DPS contribution to the 4th MPI@LHC & back-up slides of this presentation).

- **$\Delta\phi$ (also called S_ϕ(2jets))**
  - **Angle between the momenta of the extra-jets projected in the transverse plane.**
- **$\Delta^{rel}\, p_T$ (also called S_{pT}(2jets))**
  - **$|p_{jet1}+p_{jet2}|/(|p_{jet1}|+|p_{jet2}|)$ where p_{jet1} and p_{jet2} are the jet momenta projected in the transverse plane.**
- **$\Delta\, p_T$**
  - **$|p_{jet1}+p_{jet2}|$ where p_{jet1} and p_{jet2} are the jet momenta projected in the transverse plane.**
- **ΔS**
  - **Angle between total momenta of paired objects projected in the transverse plane.**
  - **Widely used in published DPS phenomenology (3jet+γ analyses)**

[FSQ-12-028]

Unfolding

- **Unfolding is performed using Bayesian method.**
- **A technique in the rooUnfold Package.**
- **Considers bin-to-bin migration in a proper way.**
- **Response Matrix and closure tests rely on several different Monte Carlo generators.**

Detector level

$p_T(\mu) > 35$ GeV, $|\eta| < 2.1$
MET > 30 GeV
Transverse Mass (W) > 50
Jets with $p_T > 20$ GeV and $|\eta| < 2.0$

unfolding

Particle level

$p_T(\mu) > 35$ GeV, $|\eta| < 2.1$
MET > 30 GeV
Transverse Mass(W) > 50
Jets with $p_T > 20$ GeV and $|\eta| < 2.0$

Same selection criteria is used for particle level and detector level

[FSQ-12-028]

Results of W + 2jets (+X) Analysis

Differential cross section and area normalized distributions corrected to particle level from data are compared to the predictions from:

- MadGraph MC events using Pythia6 with Z2* tune, and MPI on (default).
- MadGraph MC events using Pythia6 with Z2* tune, and MPI off.
- Pythia8 MC generator with 4C tune, CTEQ6L1 PDFs, MPI on (default).

Distributions in absolute scale and normalized to unit area for three different event classes:

- Exclusive two jet case, exactly two jets.
- Inclusive two jet case, leading two jets considered for calculation of DPS observables.
- Inclusive two jet case, best balancing pair of jets is considered for calulation of DPS observables.

[FSQ-12-028]

W+2jets+X : DPS Observables – Absolute normalization

Event Class : Inclusive two jet

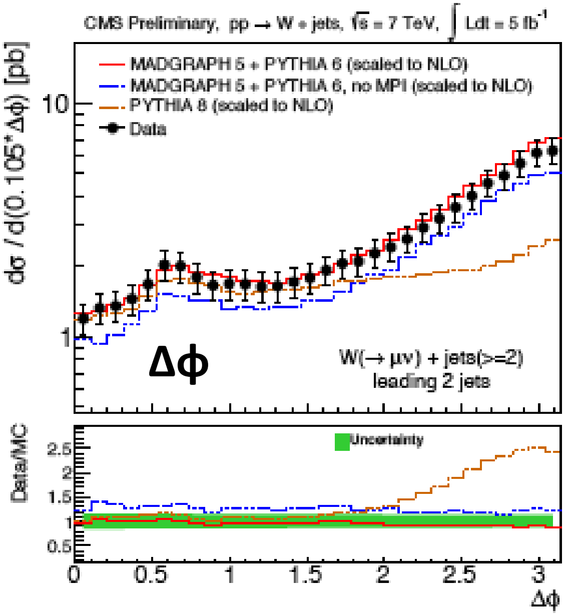
leading two jets are considered for calculation of DPS observables.

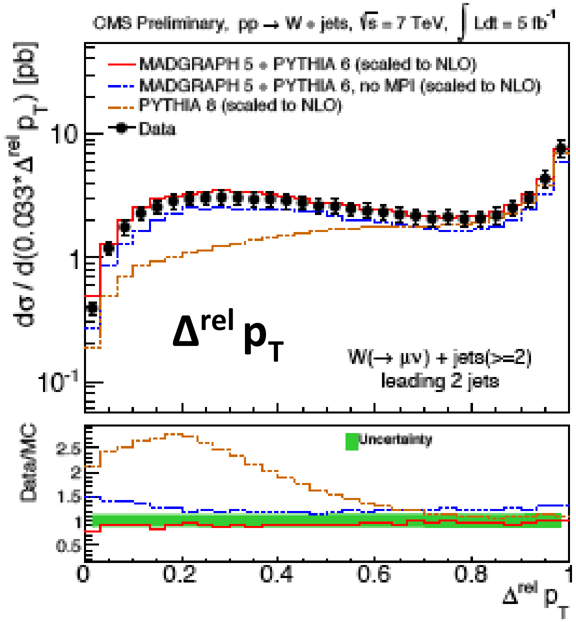
cross section for this selection
= 79.4 ± 10.8 pb

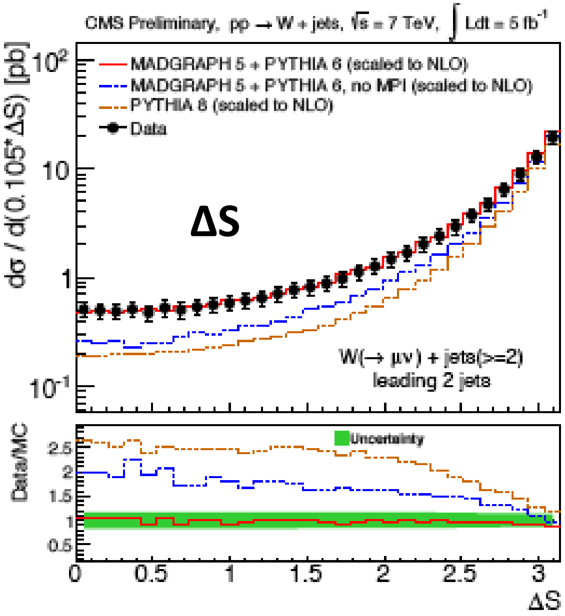
Nice agreement between data and MadGraph (+Pythia6 Z2*) with MPI on.
MadGraph with MPI off underestimates data by 18-19%.

Pythia8 underestimates data by a factor of 1.5-2 in the DPS sensitive regions, however this is mostly due to the missing higher order processes “faking” DPS.

Particle level distributions, other SM backgrounds subtracted, please compare to your favorite TH predictions!







[FSQ-12-028]

W+2jets : DPS Observables – Unit area normalization

Event Class : Exclusive two jets

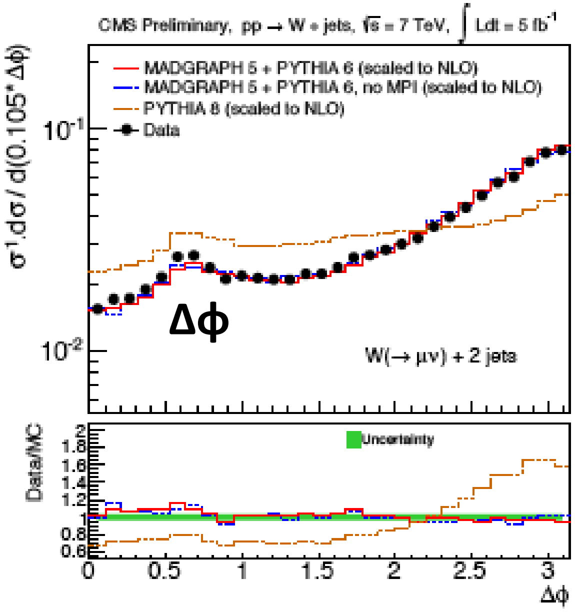
cross section = 60.6 ± 8.7 pb

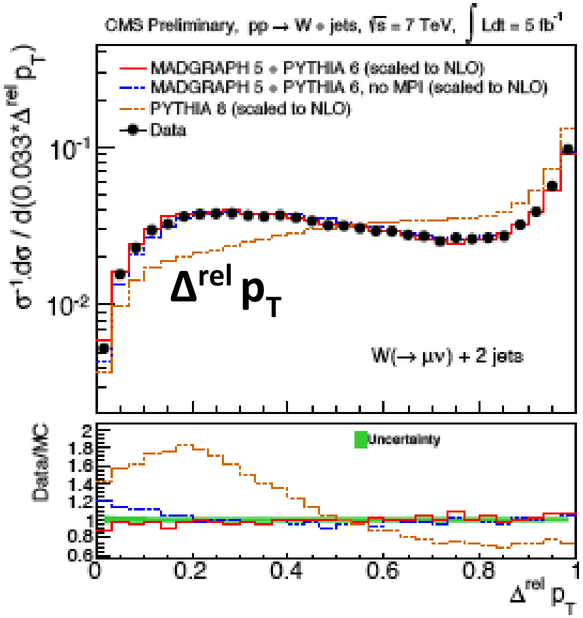
Smaller error bars due to a ≈ 1/5 reduction in the systematic uncertainties on the distributions normalized to unit area.

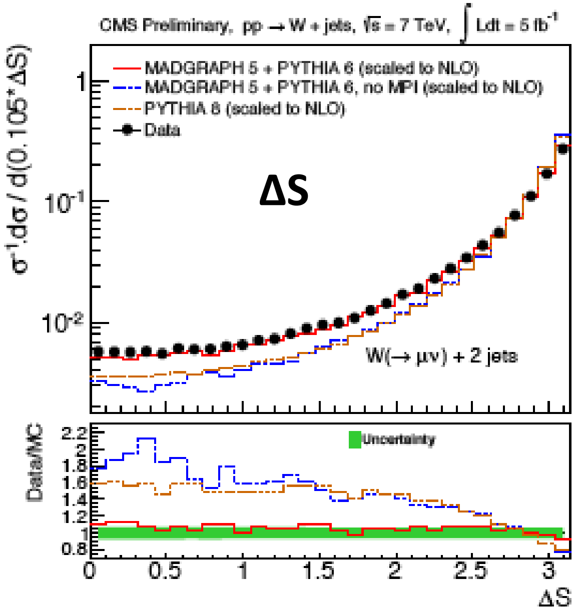
Nice agreement between data and MadGraph (+Pythia6 Z2*) with and without MPI except for the ΔS observable which is the only one capable to clearly distinguish MPI on vs MPI off for normalized distributions.

Further DPS sensitive distributions with complementary information reported in CMS PAS FSQ-12-028 and in backup slides.

Particle level distributions, other SM backgrounds subtracted, please compare to your favorite TH predictions!







Summary

- The current emphasis of Multiple Parton Interactions studies in CMS is on the Double Parton Scattering.

- A wide set of DPS-sensitive particle level observables are studied for several processes: everybody can participate to the interpretation of the results in terms of DPS content or with alternative descriptions.

- A wide set of DPS-sensitive particle level observables is already public for the W+2jets+X channel, highlights are reported in this presentation, details in CMS PAS FSQ 12-028.

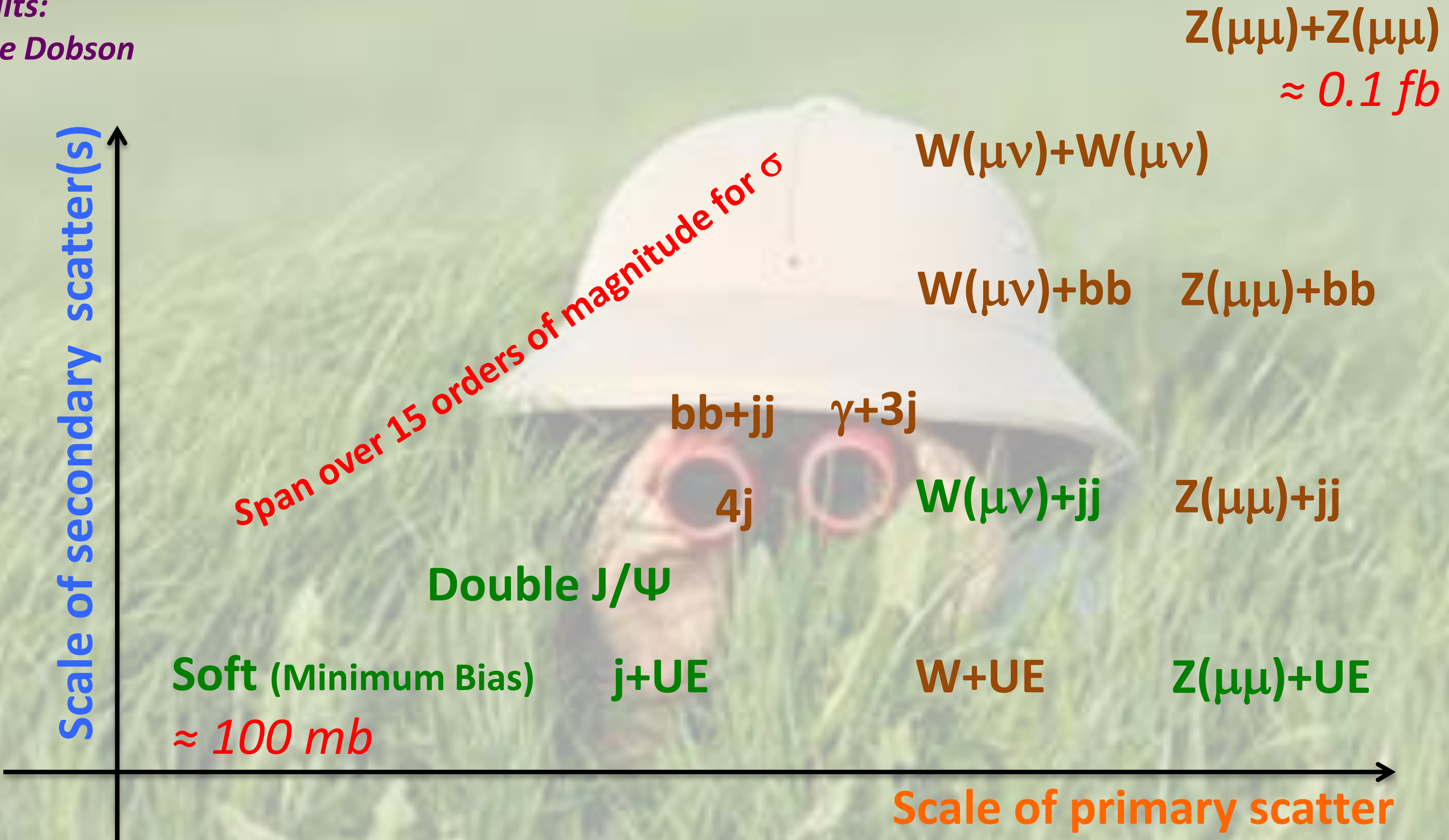
- All the observables are reported both in absolute scale and normalized to unit area, along with the the systematic uncertainties which are smaller for the latter.

- Nice agreement for all the investigated distributions is observed when comparing the data to the MadGraph generator used in conjunction with Pythia6 (Z2* tune). MPI seems to account for 18-19% of the x-section for the event selection adopted in this analysis.

- The same comparison performed on normalized distributions, indicates that only the ΔS observable keeps a clear sensitivity to Multiple Parton Interactions.

Where can we see Multiple Parton Interactions?

Credits:
- Ellie Dobson



Z(μμ)+Z(μμ)
≈ 0.1 fb

W(μν)+W(μν)

Span over 15 orders of magnitude for σ

W(μν)+bb Z(μμ)+bb

bb+jj γ+3j

4j W(μν)+jj Z(μμ)+jj

Double J/Ψ

Soft (Minimum Bias) j+UE W+UE Z(μμ)+UE
≈ 100 mb

Scale of secondary scatter(s)

Scale of primary scatter

LHC measurements available

LHC measurements not yet available

Complement with
p-A and A-A

- BACK-UP

- BACK-UP

Soft QCD - TH

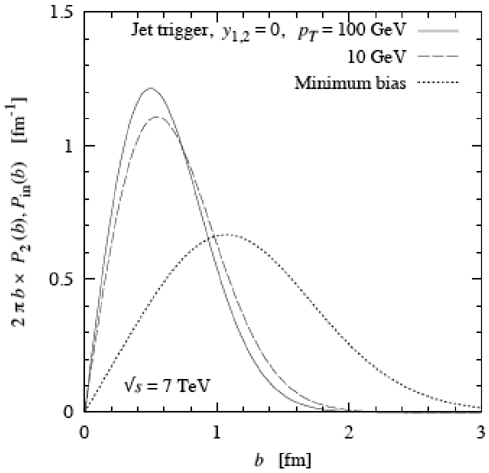
MPI vs Generalized Parton Distributions

"Inter-parton correlations and MPIs".

[M.Strikman @ this w/s and **Phys. Rev. D83 (2011) 054012**]

Gluon transverse size decreases with increase of x

$<\rho^2>_g$ from analysis of GPDs from J/ψ photo production



Impact parameter distributions of inelastic pp collisions at $\sqrt{s}$ = 7TeV. Solid (dashed) line: Distribution of events with a dijet trigger at zero rapidity, $y_{1,2}$ = 0, c, for p_T = 100 (10) GeV . Dotted line: Distribution of minimum–bias inelastic events (which includes diffraction).

Transverse size of large x partons is much smaller than the transverse range of soft strong interactions

$$\langle\rho^2\rangle_g = \frac{\partial}{\partial t}\frac{G(x.t)}{G(x,0)}$$

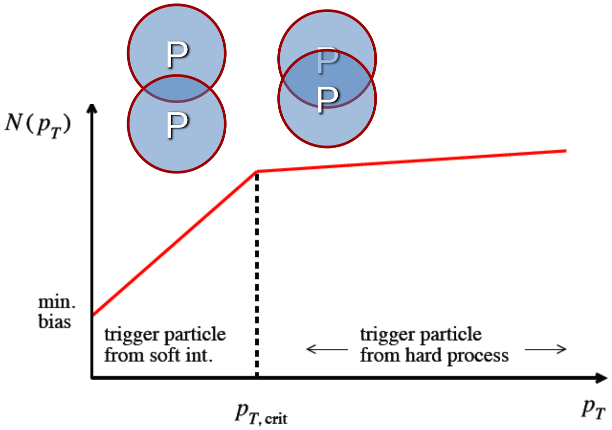
$$\langle\rho^2(x>10^{-2}\rangle \ll R^2_{soft}$$

$$\Downarrow$$

Two scale picture

Also explains general features of UE @ hadron colliders

$<\rho^2>_g$ < $<\rho^2>_q$ explains UE in DY < UE in Jets



- BACK-UP

Soft QCD CMS References relevant to MPI

1^{st} part: the basic soft QCD measurements

Focusing on Kinematics:

QCD-09-010: "Transverse momentum and pseudorapidity distributions of charged hadrons in pp collisions at $\sqrt{s}$ = 0.9 and 2.36 TeV ". J. High Energy Phys. 02 (2010) 041

QCD-10-006: "Transverse-momentum and pseudorapidity distributions of charged hadrons in pp collisions at $\sqrt{s}$ = 7 TeV ". Phys. Rev. Lett. 105 (2010) 022002

QCD-10-004: "Charged particle multiplicities in pp interactions at $\sqrt{s}$ = 0.9, 2.36, and 7.0 TeV ". J. High Energy Phys. 01 (2011) 079

QCD-10-007: "Strange particle production in pp collisions at $\sqrt{s}$ = 0.9 and 7 TeV". J. High Energy Phys. 1105:064, 2011, 1102.4282

Using also high p_T triggers to explore the tails:

QCD-10-008: "Charged particle transverse momentum spectra in pp collisions at $\sqrt{s}$ = 0.9 and 7 TeV ". J. High Energy Phys. 1108:086,2011

≈ measuring low p_T tracks and identifying hadrons in pp interactions

QCD-XX-YYY: ….

Impact on detector occupancies, pT spectra, PU features etc.

Access to deep information of the hadron structure

[QCD-XX-YYY]

2nd part: soft particle correlations

p-p

QCD-10-003: "First measurement of Bose–Einstein correlations in proton-proton collisions at √s = 0.9 and 2.36 TeV at the LHC ". Phys. Rev. Lett. 105 (2010) 032001

QCD-10-023: "Measurement of Bose–Einstein Correlations in pp Collisions at √s = 0.9 and 7 TeV at the LHC".J. High Energy Phys. 1105:029, 2011, 1101.3518

Using also large multiplicity triggers to avoid jet bias:

QCD-10-002: "Observation of Long-Range, Near-Side Angular Correlations in Proton-Proton Collisions at the LHC ". J. High Energy Phys. 09 (2010) 091

Pb-Pb

HIN-11-001: "Long-range and short-range di-hadron angular correlations in central PbPb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV". J. High Energy Phys. 1107:076,2011

HIN-11-006: "Centrality and multiplicity dependence of di-hadron correlations in PbPb and pp collisions". J. High Energy Phys. 1107 (2011) 076

p-Pb…

HIN-12-005: "Observation of long-range, near-side angular correlations in pPb collisions at the LHC". CERN-PH-EP-2012-320

≈ measuring correlations of low p_T tracks and identifying hadrons in pp interactions

QCD- or HIN- XX-YYY: ….

[QCD-XX-YYY]

3rd part: the underlying event measurements

Central Region (Tracks)

QCD-10-001: "First Measurement of the Underlying Event Activity at the LHC with $\sqrt{s}$ = 0.9 TeV". Eur. Phys. J. C 70 (2010) 555-572.

QCD-10-010: "Measurement of the Underlying Event Activity at the LHC with $\sqrt{s}$ = 7 TeV and Comparison with $\sqrt{s}$ = 0.9 TeV". JHEP 1109, 109 (2011).

QCD-10-021: "Measurement of the Underlying Event Activity with the Jet Area/Median Approach at 7 TeV and comparison to 0.9 TeV". CERN-PH-EP-2012-152, arXiv (2012), 1207.2392, submitted to JHEP.

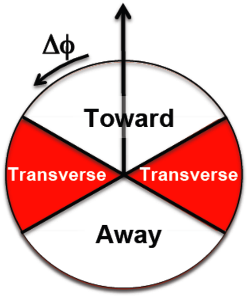
QCD-11-012: "Measurement of the Underlying Event Activity in the Drell-Yan process in proton-proton collisions at $\sqrt{s}$ = 7 TeV". CERN-PH-EP-2012-085, arXiv:1204.1411v1, submitted to Eur. Phys. J. C.

Forward Region (E-Flow)

FWD-10-008: "Forward Energy Flow, Central Charged-Particle Multiplicities, and Pseudorapidity Gaps in W and Z Boson Events from pp Collisions at 7 TeV. ". Eur.Phys.J. C72 (2012) 1839.

FWD-10-011: "Measurement of energy flow at large pseudorapidities in pp collisions at $\sqrt{s}$ = 0.9 and 7 TeV". JHEP 1111 (2011) 148, Erratum-ibid. 1202 (2012) 055.

FWD-11-003: "Study of the Underlying Event at Forward Rapidity in Proton-Proton Collisions at the LHC". CDS Record: 1434458.



≈ Measuring low p_T tracks
in phase space regions
not affected by the leading interaction

Impact on isolations, jet pedestals, vertex reco etc.
"There would not be a vertex in $H \rightarrow \gamma\gamma$ events without the Underlying Event." [QCD-10-010]
Actually UE is interesting per se!
Handle on soft MPI and beam remnants.

4th part

Hard Multiple Parton Interactions

The Double Parton Scattering (DPS)

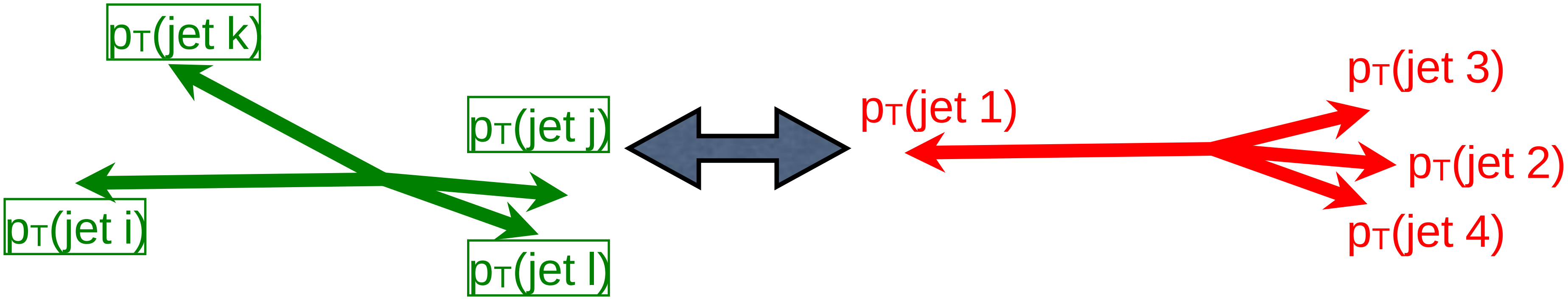
i.e. detecting patterns of two
separate hard scatterings
taking place in the same vertex

- BACK-UP

Criticisms to Tevatron 3jet + γ DPS analysis

Double Parton Scattering in 4 “objects” topologies

Disentangle double-parton-scattering from bremsstrahlung



- No correlation (DPS) vs Strong correlation (SPS)

Define different correlation angles between jet pairs:

AFS solution:

- Study Δφ between $p_{T1} - p_{T2}$ and $p_{T3} - p_{T4}$

CDF solution:

- Study Δφ between $p_{T1} + p_{T2}$ and $p_{T3} + p_{T4}$ (CDF nomenclature: ΔS)

Measurement of DPS @ Tevatron (3jet + γ)

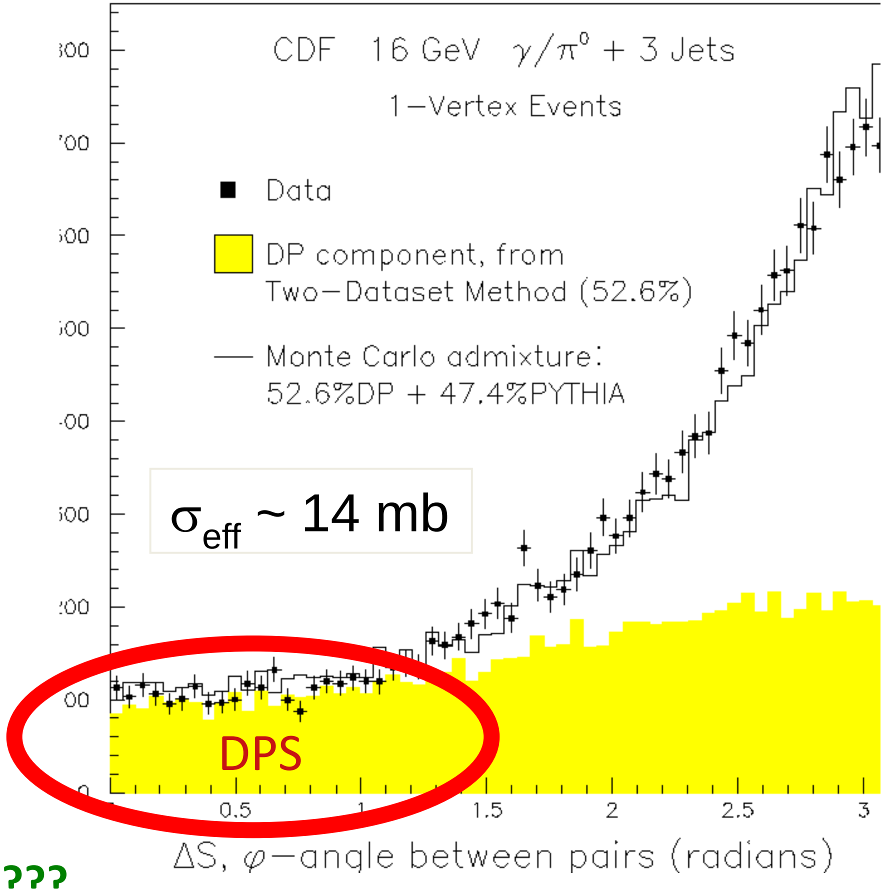
Double high P_T interactions observed by AFS, UA2, CDF, D0!!!

	CDF	LHC extrapolation
Photon	$\lvert\eta\rvert \leq 1.1$	$\lvert\eta\rvert \leq 2.5$
	$E_T \geq 16$ GeV	$E_T \geq 50$ GeV
	Cone $R = 0.7$	$k_\perp$ $D = 0.4$
Jets	$\lvert\eta\rvert \leq 4.2$	$\lvert\eta\rvert \leq 5$
	$E_T \geq 5$ GeV	$E_T \geq 20$ GeV
	$E_{T4} < 5$ GeV	$E_{T4} < 10$ GeV
	$E_{T2}, E_{T3} < 7$ GeV	$E_{T2}, E_{T3} < 30$ GeV

Are the SIGNAL and BACKGROUND simulations used in this analysis reliable?

RECO vs TRUE: is a DPS event "just below" threshold SIGNAL or BACKGROUND???

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



σ_{eff} ~ 14 mb

σ_{eff} ~ 11 mb [Treleani et al., PRD76:076006,2007] based on the CDF paper (+ triple interactions)

σ_{eff} ~ 16 mb [D0 collaboration Phys.Rev. D81 (2010) 052012]

Are the Tevatron DPS results reliable?

- **Direct photon single parton scattering (SPS) processes with three extra jets are not included in the general purpose Monte Carlo models used to simulate the background.**

- **Ongoing activity to re-interpret the 3jet + γ Tevatron data**

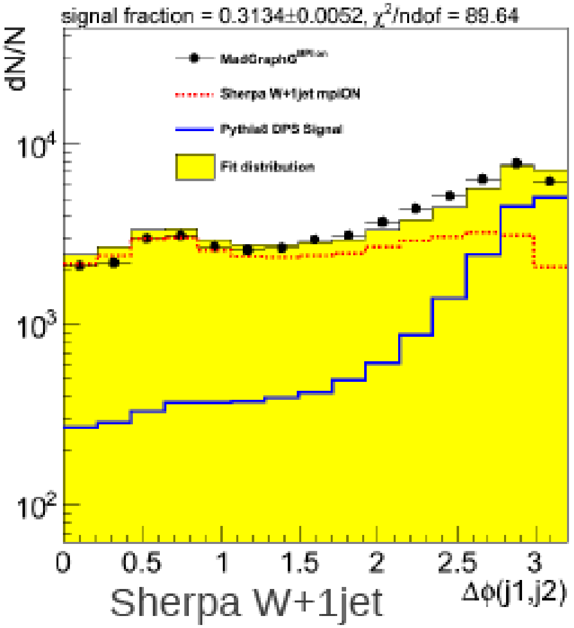
- BACK-UP

CMS DPS Contribution @ 4th MPI@LHC

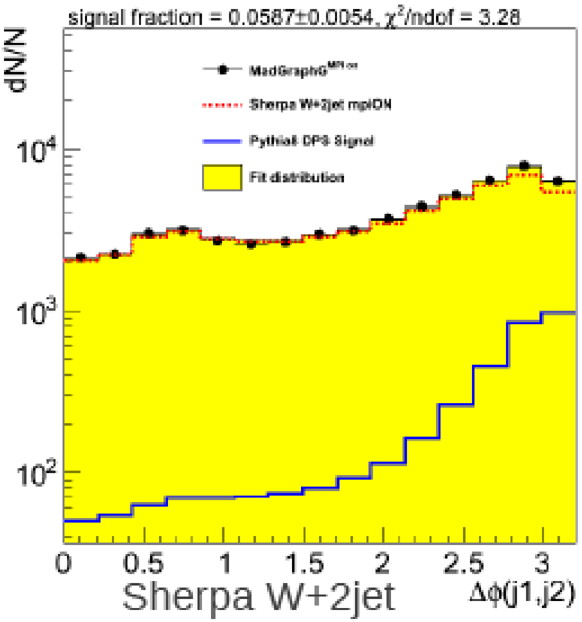
W+2jets pseudo-data experiement (MG W+4jets, MPI on)

Background = Sherpa W+njets with MPI on, Signal = Pythia 8 W+2jets DPS
Fitted Signal fraction and reduced χ^2 reported in the table

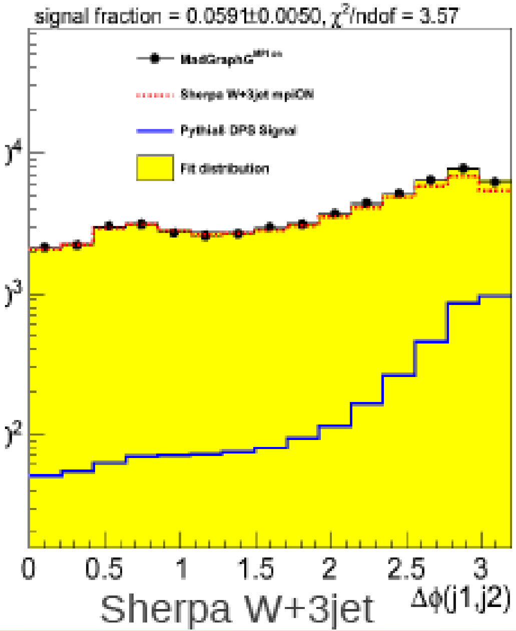
Background:	dphi	dpt	dS
Sherpa W+0 jet mpi on	17.05+-0.75, 15.18	5.32+-0.48, 25.14	8.32+-0.41, 40.51
Sherpa W+1jet mpi on	31.34+-0.52, 89.64	23.16+-0.031, 286.29	9.84+-0.030, 32.24
Sherpa W+2jet mpi on	**5.87+-0.54, 3.28**	**6.68+-0.29, 5.81**	**5.55+-0.25, 2.64**
Sherpa W+3jet mpi on	**5.91+-0.50, 3.57**	**6.66+-0.29, 5.09**	**3.48+-0.25, 0.90**



Sherpa W+1jet



Sherpa W+2jet



Sherpa W+3jet

W+2jets pseudo-data experiement (MG W+4jets, MPI on)

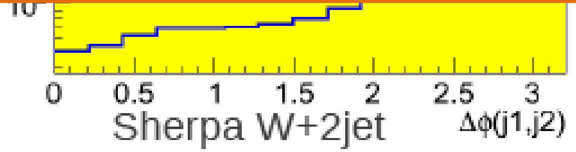
Background = Sherpa W+njets with MPI on, Signal = Pythia 8 W+2jets DPS

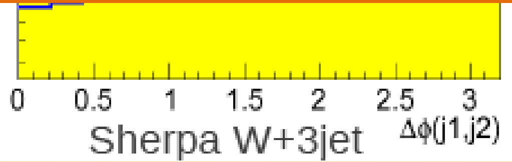
Fitted Signal fraction and reduced χ^2 reported in the table

Background:	dphi	dpt	dS
Sherpa W+0 jet mpi on	17.05+-0.75, 15.18	5.32+-0.48, 25.14	8.32+-0.41, 40.51
Sherpa W+1jet mpi on	31.34+-0.52, 89.64	23.16+-0.031, 286.29	9.84+-0.030, 32.24
Sherpa W+2jet mpi on	**5.87+-0.54, 3.28**	**6.68+-0.29, 5.81**	**5.55+-0.25, 2.64**
Sherpa W+3jet mpi on	**5.91+-0.50, 3.57**	**6.66+-0.29, 5.09**	**3.48+-0.25, 0.90**

Conclusions:

- Uncertainties and bad fit seen for W+0jet, W+1jet indicate that we can trust only ME tools having at least 2 extra emissions → general purpose MCs ruled out.
- Identical results in rows for W+2jet and W+3jet indicate that adding the 3rd emmission does not affect the results in a significant way.
- Fitted signal fraction significantly different from 0% means that Sherpa and Madgraph tunes have different intrinsic DPS content. MadGraph+tune has more DPS than Sherpa+DPS.
- The choice of the observable influence the fraction.





W → $l\nu$ + 2 jets analysis, lessons learnt

✓ **Important prescriptions applying also to other DPS analyses:**

- **The choice of the DPS observable is an important source of systematics.**

-**The single parton scattering background should include enough extra-emissions described with a Matrix Element tool. The usage of a general purpose Monte Carlo for the background description may end-up strongly overestimating the DPS signal fractions.**

- **SIGNAL + BACKGROUND should cover the full phase space.**

- **When looking for an extra di-jet interaction at a given p_T from DPS whatever is below such scale should be considered BACKGROUND even in the case it comes from DPS.**

Experience with Double Parton Scattering studies @ LHC / LIC

Connection to the DPS theory

- The effective x-section (σ_{eff}) should be regarded as the most natural link to the theories.
- $\sqrt{s}$ and scale (in)dependency should not be assumed, it should rather be tested/measured although the first benchmark measurements should focus on simple working points.
- Process dependency is studied regarding the global picture of DPS measurements.
- Inclusive measurements.

→Get rid of those cuts which select “one and only one” additional interaction!!! Triple, interactions should be retained as well!

→Let’s use more than one DPS observable, quoting the corresponding systematic uncertainty.

MC matters, it is the only way to define SIGNAL and BACKGROUNDS in DPS analyses

- It is desirable to have more generator level studies to quote the effect of extra-emissions (Matrix Element tools) and softer showers: how DPS signals are diluted?
- At the same time it is ESSENTIAL to use appropriate DPS SIGNAL (Pythia8, Herwig++, etc.).
- BACKGROUND **IS NOT MPI OFF (or DPS off) IT IS RATHER “2nd interaction below a given p_T”.**
- **ALWAYS MAKE SURE** that SIGNAL+BACKGROUND(S) cover the full phase space.
- Algebra may help to use only SIGNAL and INCLUSIVE samples provided σ_{eff}(MC) is known
- Warning: σ_{eff}(MC) of inclusive samples may differ w.r.t. the one of exclusive samples (SIGNAL).

→Let’s use more than one MC, quoting the corresponding systematic uncertainty.

- BACK-UP

CMS PAS FSQ-12-028: DPS in W + 2jets (+X)

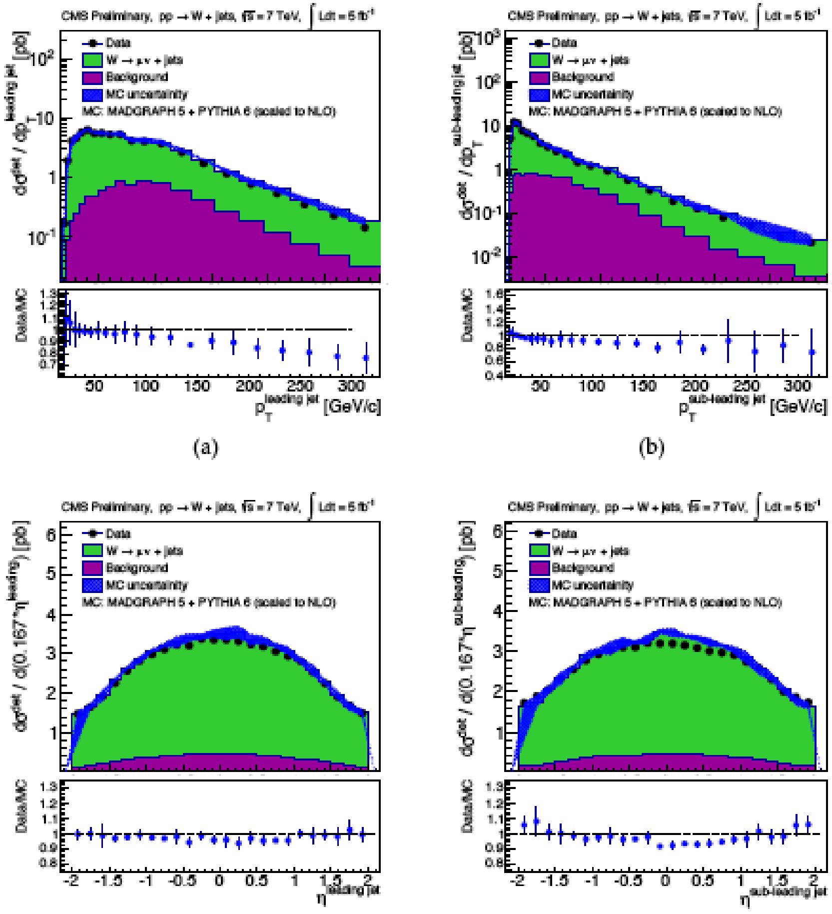
Number of events after selection

Number of events after selection of W + 2 jets, corresponding to integrated luminosity of 5.0 fb^{-1}

Sample	**Exclusive selection (exactly 2 jets)**		**Inclusive selection (at least 2 jets)**	
	Events	**Relative contribution(%)**	**Events**	**Relative contribution(%)**
Data	243803	-	315096	-
W→μ+ν	228761	91.5	284439	87.6
W→τ+ν	3723	1.48	4736	1.46
DY	5301	2.12	6564	2.02
QCD	350	0.14	467	0.14
WW/WZ	2564	1.02	3463	1.07
top	**9360**	**3.74**	**25210**	**7.76**

- **Major contribution is from top backgrounds.**
- **QCD contribution is negligibly small.**

Control plots



(a) (b)

(c) (d)

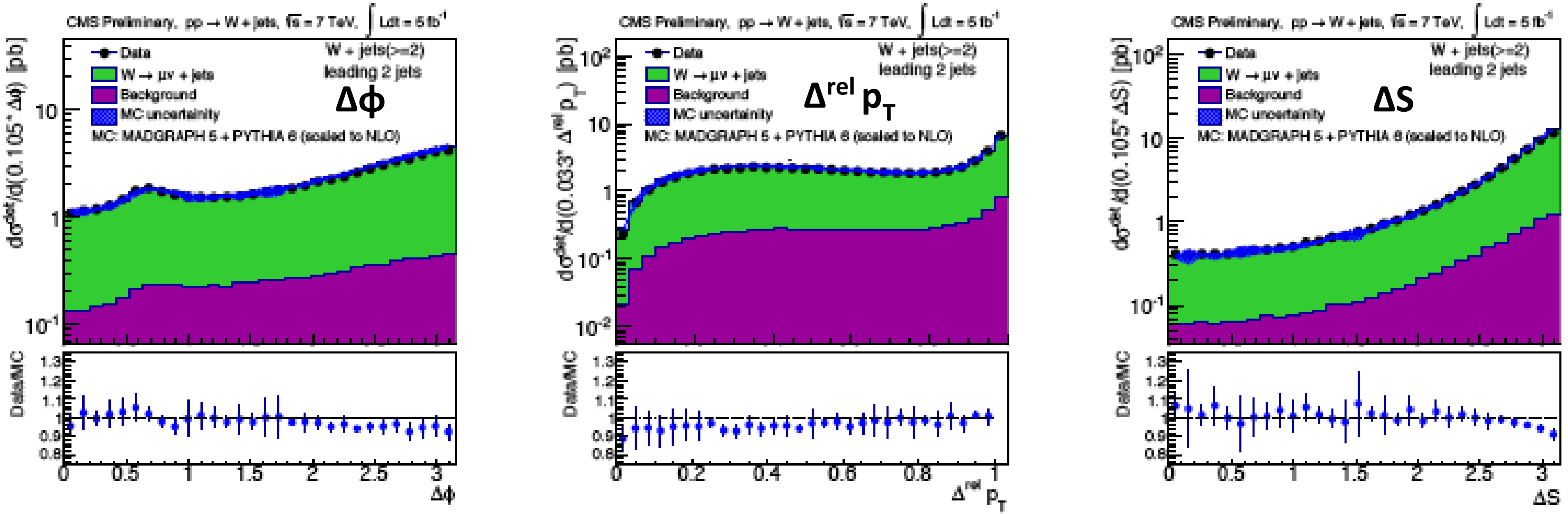
Figure 2: Detector-level comparison of data with MC simulations for the transverse momentum (top row) and pseudo-rapidity (bottom row) of leading (left column) and sub-leading (right column) jets. Simulation uncertainty includes systematic due to variation of matching and factorization scales. This band also includes uncertainty on theoretical cross sections quoted in Table 1.

Kinematic distributions of the First two jets.

DPS Observables – Detector level distributions

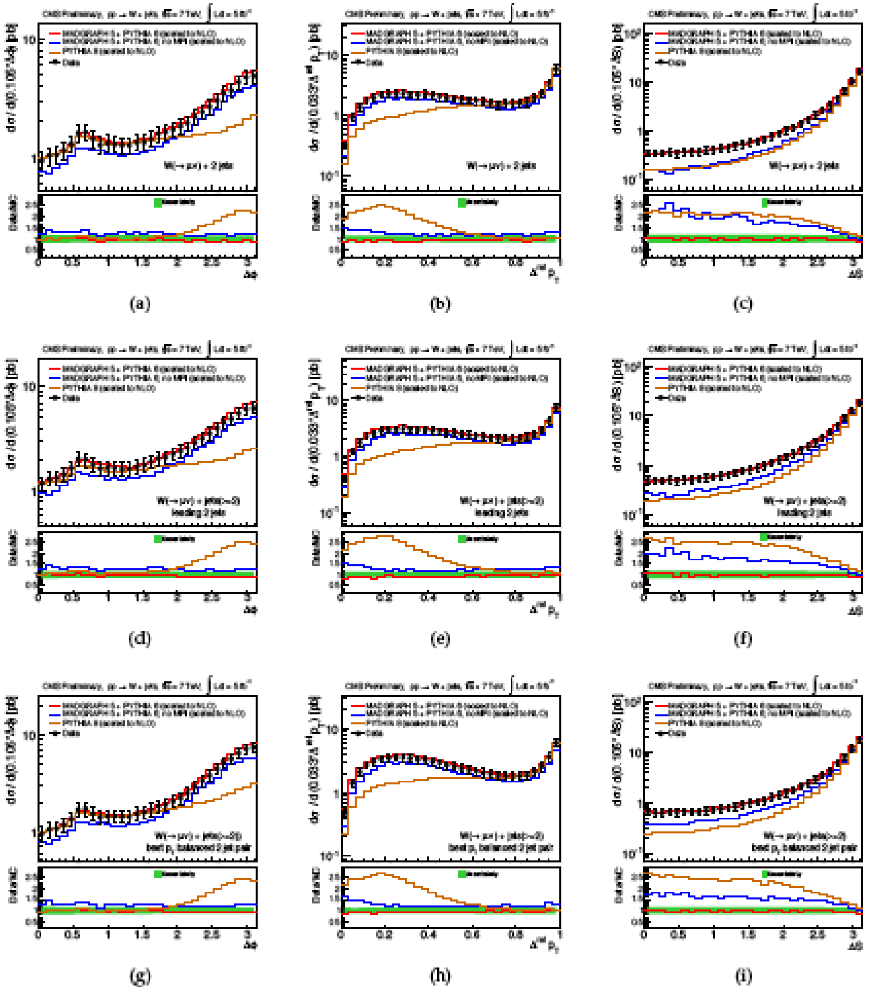
Event Class : Inclusive two jets

leading two jets are considered for calculation of DPS observables.



Nice agrement b/w data and MC

DPS Distributions (absolute normalization)



(a) (b) (c)

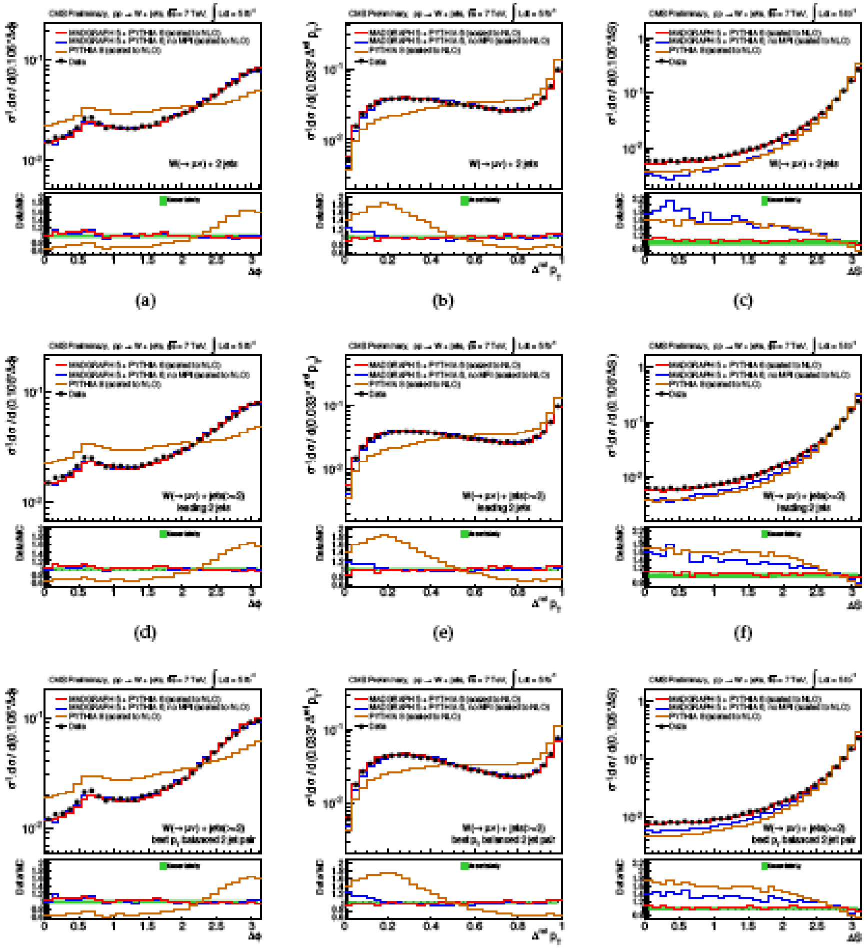
(d) (e) (f)

(g) (h) (i)

Figure 4: Fully corrected differential cross sections for various DPS-sensitive observables: $\Delta\phi$ (left), $\Delta^{\mathrm{rel}} p_T$ (centre), and ΔS (right). The comparison is shown for three event classes: exactly two jets (top row), at least two jets with the leading two jets used to calculate DPS observables (centre row) and with the jet pair which is best balanced in p_T (bottom row). The bottom pad in each plot shows the ratio of data over simulations. The green band represents the total uncertainty in the experimental distribution.

Particle level

DPS Distributions normalized to unit area



(a) (b) (c)

(d) (e) (f)

(g) (h) (i)

Figure 5: Fully corrected data distributions, normalized to unity, of DPS-sensitive observables $\Delta\phi$ (left), $\Delta^{rel} p_T$ (centre), and ΔS (right). The comparison is shown for three event classes: exactly two jets (top row), at least two jets with the leading two jets used to calculate DPS observables (centre row) and with the jet pair which is best balanced in p_T (bottom row). The bottom pad in each plot shows the ratio of data over simulations. The green band represents the total uncertainty in the experimental distribution.

Particle level

Systematic uncertainties

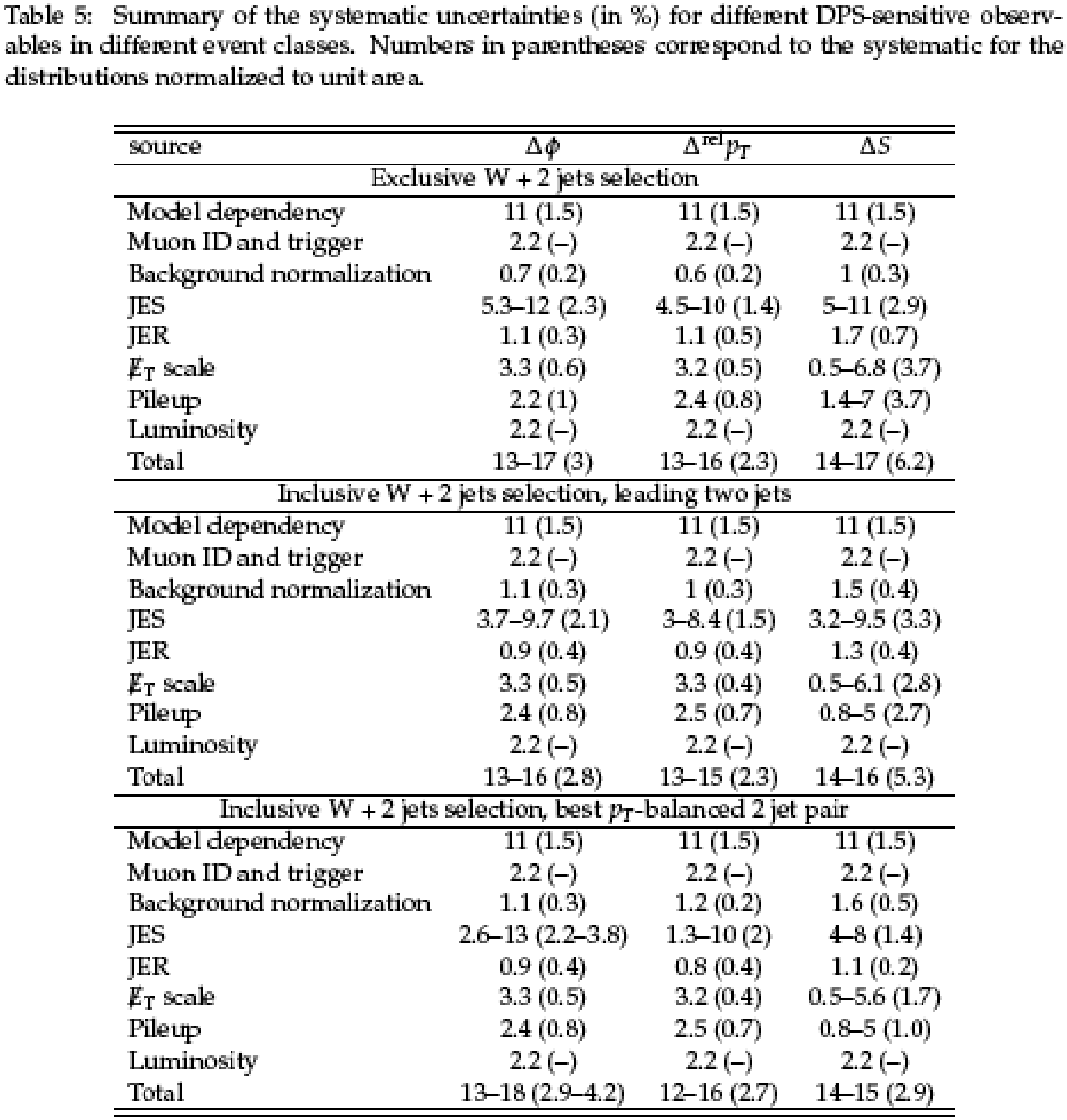


Table 5: Summary of the systematic uncertainties (in %) for different DPS-sensitive observables in different event classes. Numbers in parentheses correspond to the systematic for the distributions normalized to unit area.

source	$\Delta\phi$	$\Delta^{\text{rel}} p_T$	ΔS
Exclusive W + 2 jets selection			
Model dependency	11 (1.5)	11 (1.5)	11 (1.5)
Muon ID and trigger	2.2 (–)	2.2 (–)	2.2 (–)
Background normalization	0.7 (0.2)	0.6 (0.2)	1 (0.3)
JES	5.3–12 (2.3)	4.5–10 (1.4)	5–11 (2.9)
JER	1.1 (0.3)	1.1 (0.5)	1.7 (0.7)
$\not\!\!E_T$ scale	3.3 (0.6)	3.2 (0.5)	0.5–6.8 (3.7)
Pileup	2.2 (1)	2.4 (0.8)	1.4–7 (3.7)
Luminosity	2.2 (–)	2.2 (–)	2.2 (–)
Total	13–17 (3)	13–16 (2.3)	14–17 (6.2)
Inclusive W + 2 jets selection, leading two jets			
Model dependency	11 (1.5)	11 (1.5)	11 (1.5)
Muon ID and trigger	2.2 (–)	2.2 (–)	2.2 (–)
Background normalization	1.1 (0.3)	1 (0.3)	1.5 (0.4)
JES	3.7–9.7 (2.1)	3–8.4 (1.5)	3.2–9.5 (3.3)
JER	0.9 (0.4)	0.9 (0.4)	1.3 (0.4)
$\not\!\!E_T$ scale	3.3 (0.5)	3.3 (0.4)	0.5–6.1 (2.8)
Pileup	2.4 (0.8)	2.5 (0.7)	0.8–5 (2.7)
Luminosity	2.2 (–)	2.2 (–)	2.2 (–)
Total	13–16 (2.8)	13–15 (2.3)	14–16 (5.3)
Inclusive W + 2 jets selection, best p_T-balanced 2 jet pair			
Model dependency	11 (1.5)	11 (1.5)	11 (1.5)
Muon ID and trigger	2.2 (–)	2.2 (–)	2.2 (–)
Background normalization	1.1 (0.3)	1.2 (0.2)	1.6 (0.5)
JES	2.6–13 (2.2–3.8)	1.3–10 (2)	4–8 (1.4)
JER	0.9 (0.4)	0.8 (0.4)	1.1 (0.2)
$\not\!\!E_T$ scale	3.3 (0.5)	3.2 (0.4)	0.5–5.6 (1.7)
Pileup	2.4 (0.8)	2.5 (0.7)	0.8–5 (1.0)
Luminosity	2.2 (–)	2.2 (–)	2.2 (–)
Total	13–18 (2.9–4.2)	12–16 (2.7)	14–15 (2.9)

- BACKUP

FUTURE

Some DPS figures for pp at √s = 14 TeV

- σ_{DPS} **(4jets@100 GeV)** $= ½ * (\sigma\ (2\text{jets}))^2/\sigma_{eff}$
$= ½ * (1\mu b)^2/\sigma_{eff} = 5\ 10^{-5}\ \mu b =$ **50 pb**
  - apply extra **1%** factor for each b-jet pair requirement
- σ_{DPS} **(4γ@20 GeV)** $= ½ * (\sigma\ (2\gamma))^2/\sigma_{eff}$
$= ½ * (0.1\mu b)^2/\sigma_{eff} = 5\ 10^{-5}\ \mu b =$ **0.5 pb**

Present

- σ_{DPS} **($W^\pm \rightarrow \mu\nu$, $W^\pm \rightarrow \mu\nu$)** $= ½ * (\sigma\ (W^\pm \rightarrow \mu\nu))^2/\sigma_{eff}$
$= ½ * (20nb)^2/\sigma_{eff} = 2\ 10^{-5}\ nb =$ **20 fb**
  - half of which (**10 fb**) corresponds to same sign muons
- σ_{DPS} **($Z \rightarrow \mu\mu$, $Z \rightarrow \mu\mu$)** $= ½ * (\sigma\ (Z \rightarrow \mu\mu))^2/\sigma_{eff}$
$= ½ * (2nb)^2/\sigma_{eff} = 2\ 10^{-7}\ nb =$ **0.2 fb**

Future, including HL-LHC

$\sigma_{eff} = 10$ mb is assumed to allow for possible easy rescaling