MPI Results from the LHC

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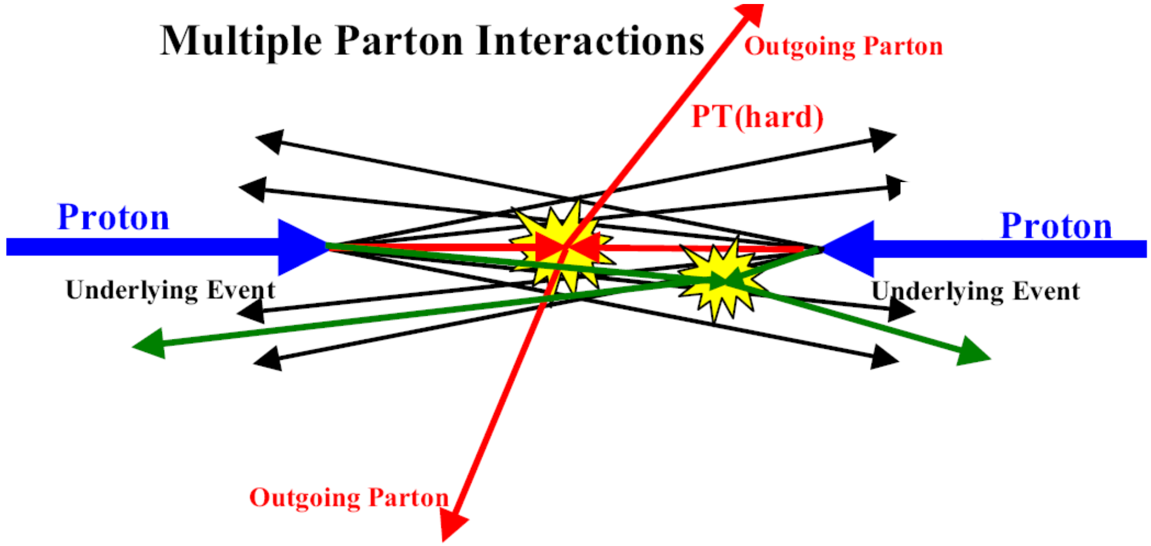
Multiparton Interactions



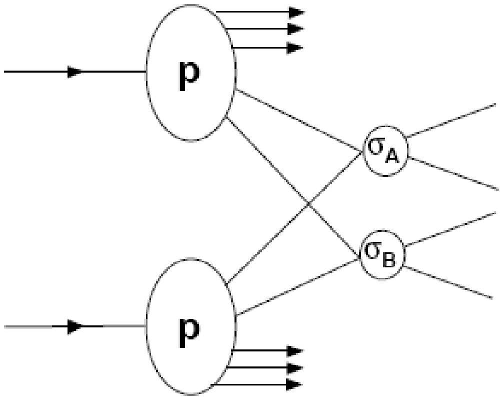
Soft QCD measurements → see talk by Michael Heinrich

Here focus on **Double Parton Interactions**

- DPS cross-section
- Prospects and measurements on DPS with jets in final state
- Prospects and measurements on DPS with lepton final states
- DPS in PbPb collisions

MPI at High-pT

- multiple parton interactions play an important role in hadron-hadron collisions at high energies and are one of the most common, yet poorly understood phenomenon at the LHC



Assume factorization of A and B:

$$\sigma_{DPS}^{AB} = \frac{m}{2} \sum_{i,j,k,l} \int \Gamma_{ij}(x_1, x_2; \mathrm{b}_1, \mathrm{b}_2; Q_1^2, Q_2^2) \hat{\sigma}_{ik}^{A}(x_1, x_1^{'}, Q_1^2) \hat{\sigma}_{jl}^{B}(x_2, x_2^{'}, Q_2^2)$$

$$\times \Gamma_{kl}(x_1^{'}, x_2^{'}; \mathrm{b}_1 - \mathrm{b}, \mathrm{b}_2 - \mathrm{b}; Q_1^2, Q_2^2) \times dx_1 dx_2 dx_1^{'} dx_2^{'} d^2b_1 d^2b_2 d^2b,$$

Factorization of longitudinal & transverse components and two parton distributions =>

$$\sigma_{\mathrm{DPS}}^{\mathrm{AB}} = \frac{m}{2} \frac{\sigma_{\mathrm{SPS}}^{A} \sigma_{\mathrm{SPS}}^{B}}{\sigma_{\mathrm{eff}}}$$

$\sigma_{\mathrm{SPS}}^{A}$ = inclusive cross section of single hard scattering

σ_{eff} = non-perturbative quantity related to transverse size of hadrons

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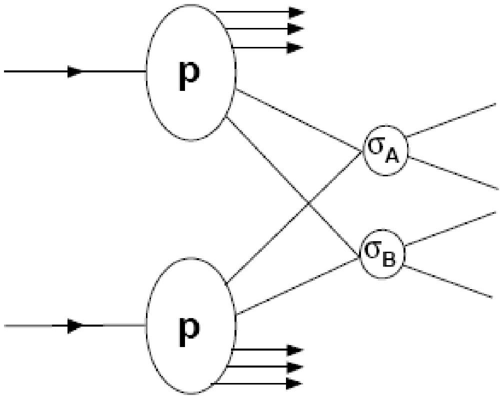

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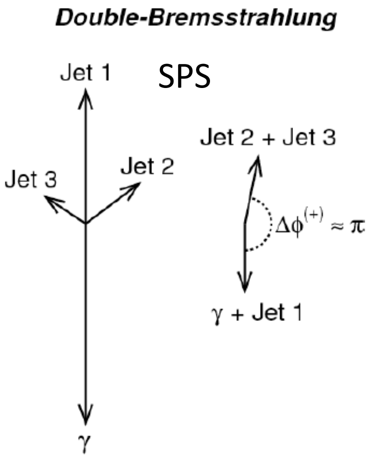
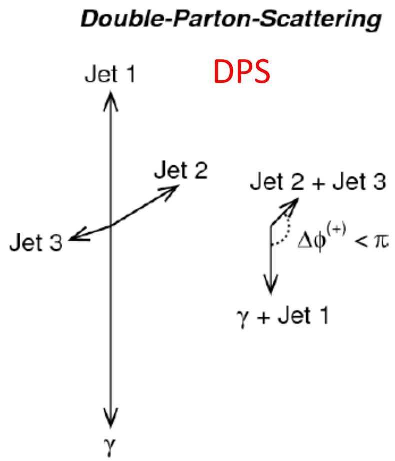
>correlations btw parton distributions may change this simple relation of σ_{DPS}<

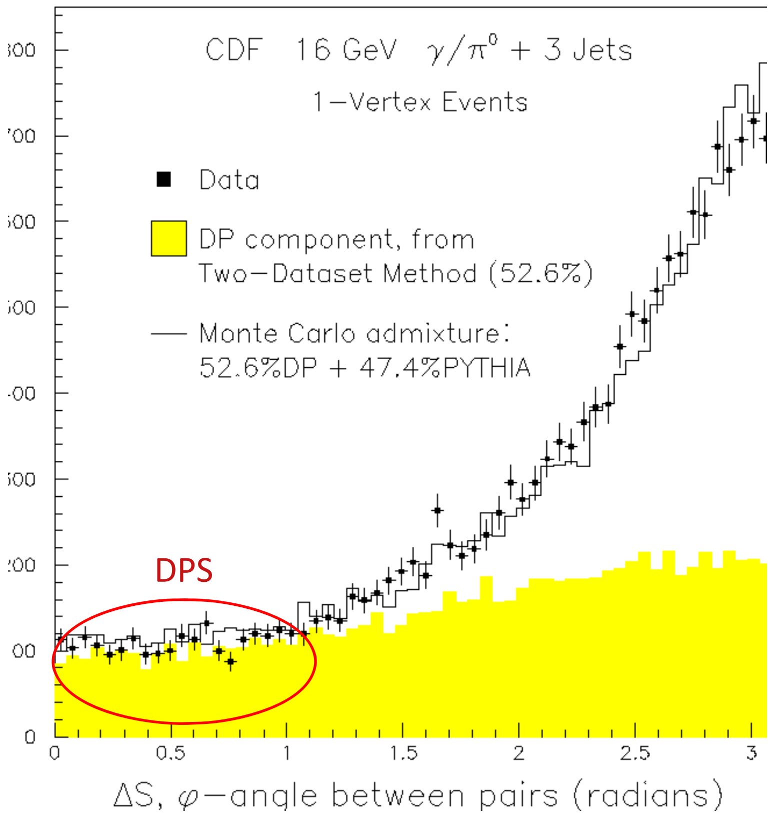
DPI and Jets

- the presence of multiple parton interactions in high-energy hadronic collisions has been convincingly demonstrated by the AFS, UA2, CDF and D0 Collaborations, using events with the four-jets and gamma + 3-jets final states





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

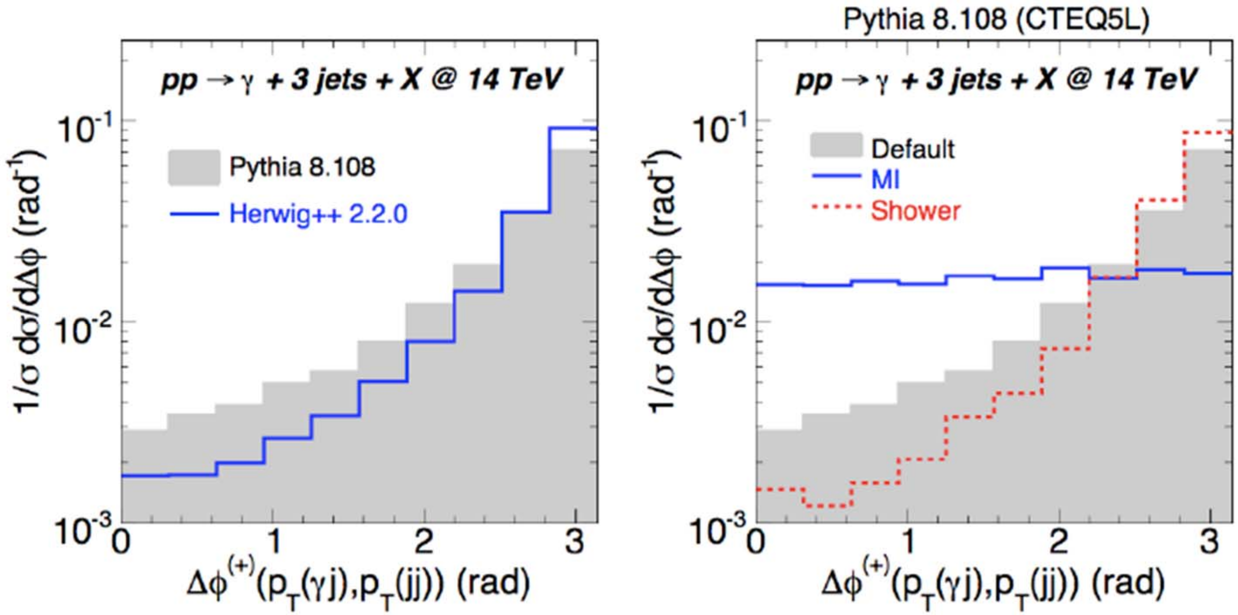


No correlation (DPS) vs Strong Correlation (SPS)

- discriminating variable: $\Delta\phi$ between $p_{T1} + p_{T2}$ and $p_{T3} + p_{T4}$

DPI and Jets

$$\Delta\phi^{(+)} = \angle\left(\vec{p}_T^{\,\gamma} + \vec{p}_T^{\,1}, \vec{p}_T^{\,2} + \vec{p}_T^{\,3}\right)$$



default = PYTHIA out of the box
MI = parton showers switched off
Shower = MI switched off

Differential cross-section shape predictions for $\Delta\phi$

- discrimination power clearly visible (shower scenario vs MI scenario)

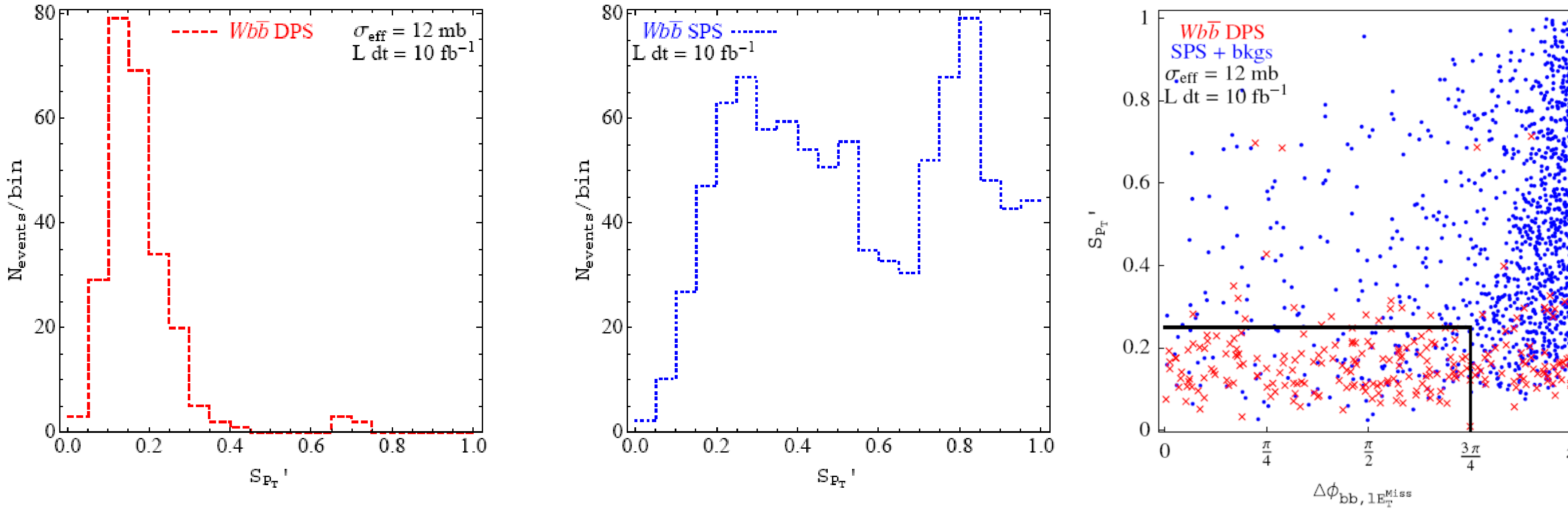
DPI and Jets: Wbb at NLO

$$d\sigma^{DPS}(pp \to Wb\bar{b}X) = \frac{d\sigma(pp\to WX)d\sigma(pp\to b\bar{b}X)}{\sigma_{\rm eff}}$$

E. Berger, C. Jackson, S. Quackenbush, G. Shaughnessy
[arXiv: 1107.3150]

- new physics often has W or bb final states
- bb has large CS (μb)
- W easy to identify (lepton+mising energy)

$$S'_{p_T} = \frac{1}{\sqrt{2}}\sqrt{\left(\frac{|p_T(b_1,b_2)|}{|p_T(b_1)|+|p_T(b_2)|}\right)^2 + \left(\frac{|p_T(\ell,\not{E}_T)|}{|p_T(\ell)|+|\not{E}_T|}\right)^2}$$



In DPS: bottom quarks produced back-to-back

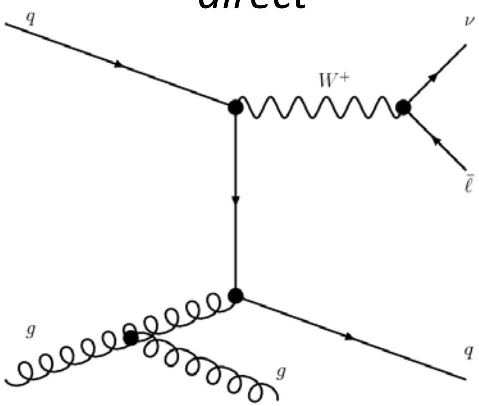
In SPS: bottom quarks are not back-to-back

S'_{p_T} and $\Delta\phi_{bb,\ell\not{E}_T}$ can differentiate DPS from SPS at excellent significance (>12σ)

W → lν + 2 jets

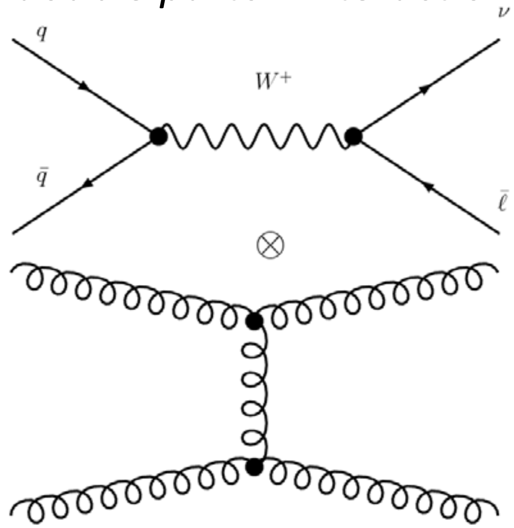
Production of W bosons in association with two jets in pp has been investigated by ATLAS

direct



$$d\sigma_{W+2j}^{(tot)}(s) = d\sigma_{W+2j}^{(dir)}(s) + d\sigma_{W+2j}^{(DPI)}(s)$$

double parton interaction



$$f_{\mathrm{DP}}^{\mathrm{R}} = \frac{N_{W_0+2\mathrm{j}_{\mathrm{DPI}}}}{N_{W+2j}}$$

$$\sigma_{eff} = \frac{1}{f_{DP}^{R}} \cdot \frac{N_{W_0} N_{2j}}{N_{W+2j}} \cdot \frac{1}{\varepsilon_{2j} L_{2j}}$$

- measure fraction of $W_0 + 2j_{DPI}$ in the *W+2jet* sample (f^R_{DP})
  - use difference in kinematics (p_T, …)
- σ_{eff}

W selection
Single lepton trigger
1 lepton (e, μ) $p_T > 20$ GeV, $\eta < 2.5$
MET > 25 GeV, $m_T > 40$ GeV
2 jets, $p_T > 20$ GeV, $|y| < 2.8$

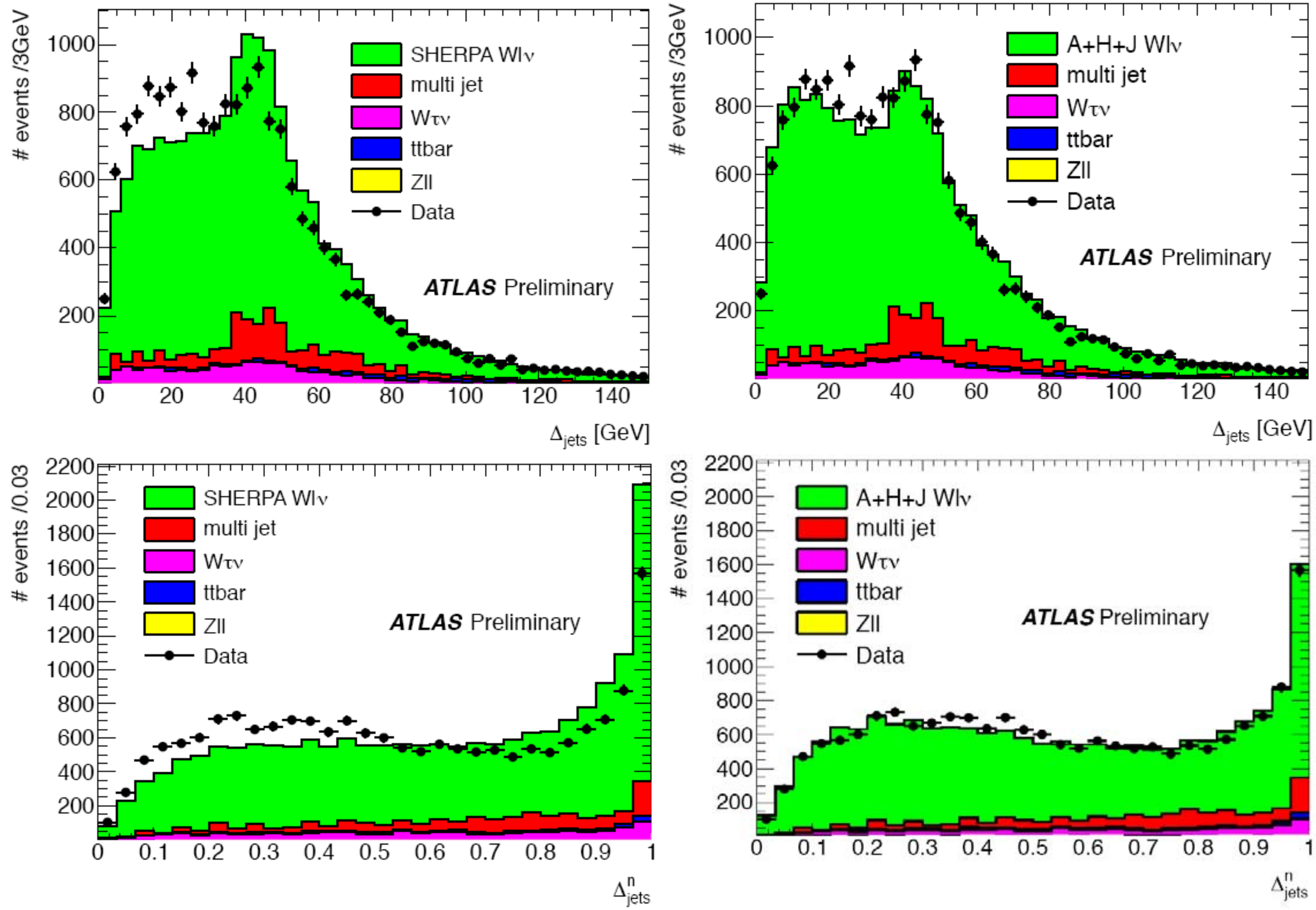
Jet selection
Minimum bias trigger
2 jets, $p_T > 20$ GeV, $|y| < 2.8$

W → lν + 2 jets : Topology

$$\Delta_{jets} = \left| \overrightarrow{p_T}^{J1} + \overrightarrow{p_T}^{J2} \right|$$

- parameterises degree of transverse separation btw jets

$$\Delta^n_{jets} = \frac{\left| \overrightarrow{p_T}^{J1} + \overrightarrow{p_T}^{J2} \right|}{\left| \overrightarrow{p_T}^{J1} \right| + \left| \overrightarrow{p_T}^{J2} \right|}$$

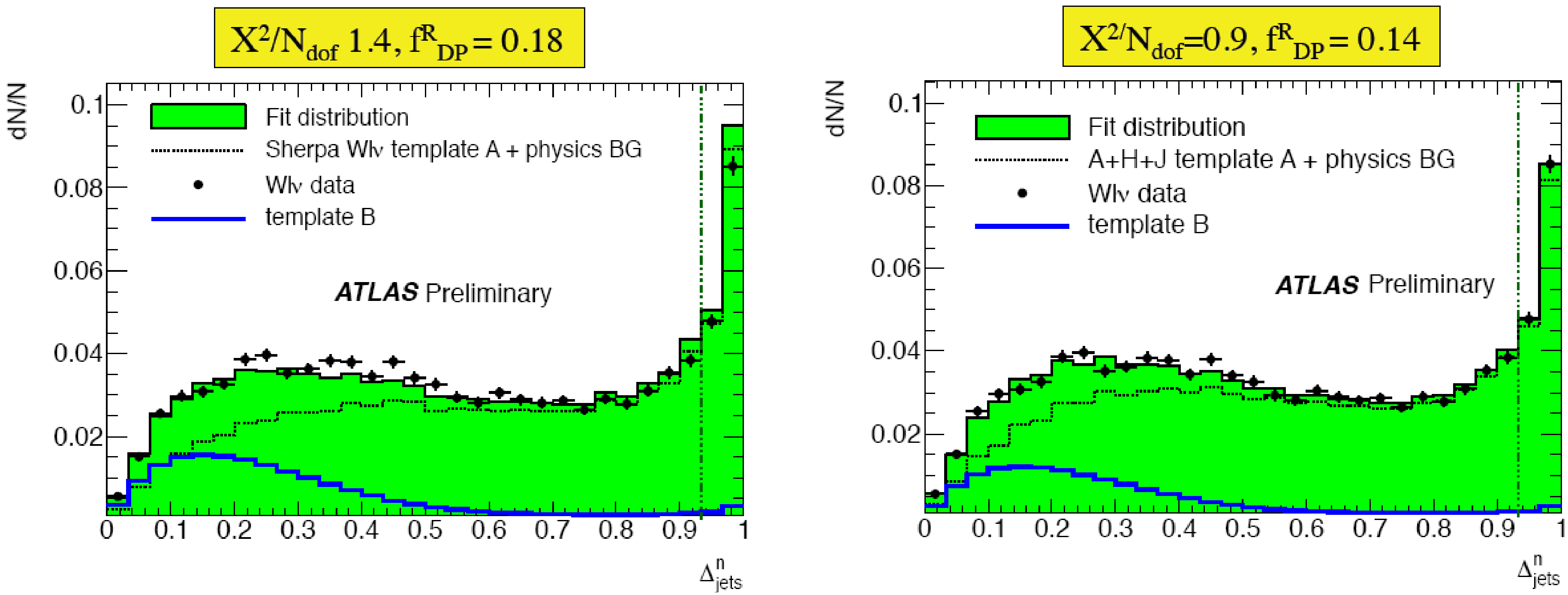


– Δ^n_{jets} selected to perform the fit over (more stable wrt jet energy)
- Alpgen+Herwig+Jimmy (default DPI settings) describe data well, Sherpa not so good

W → lν + 2 jets : DPI Rate

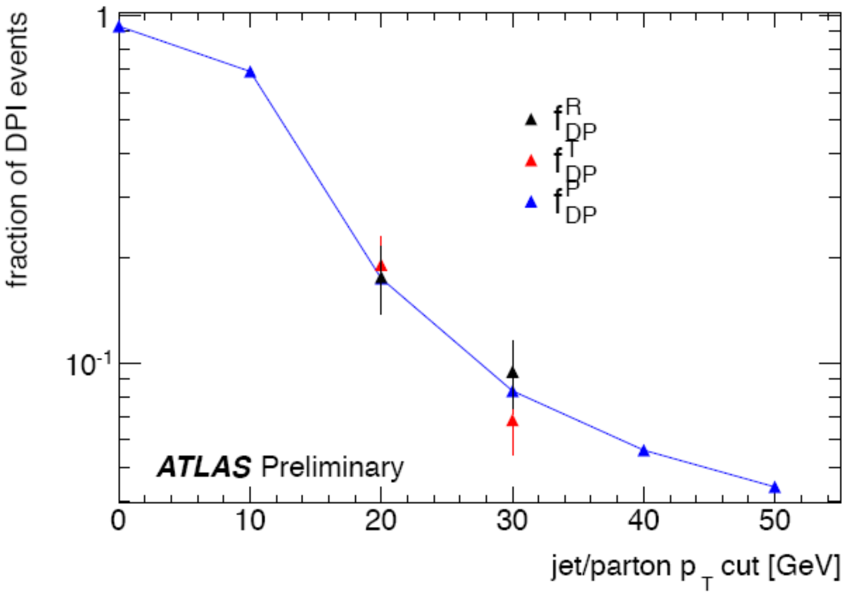
- Extraction of f^R_{DP} using fit to data with two templates
- Template A (nonDPI sample): both jets originate from the primary scatter
- Template B (a DPI sample) : both jets originate from the DPI scatter

$$(1-f^R_{DP})\cdot A + f^R_{DP}\cdot B$$



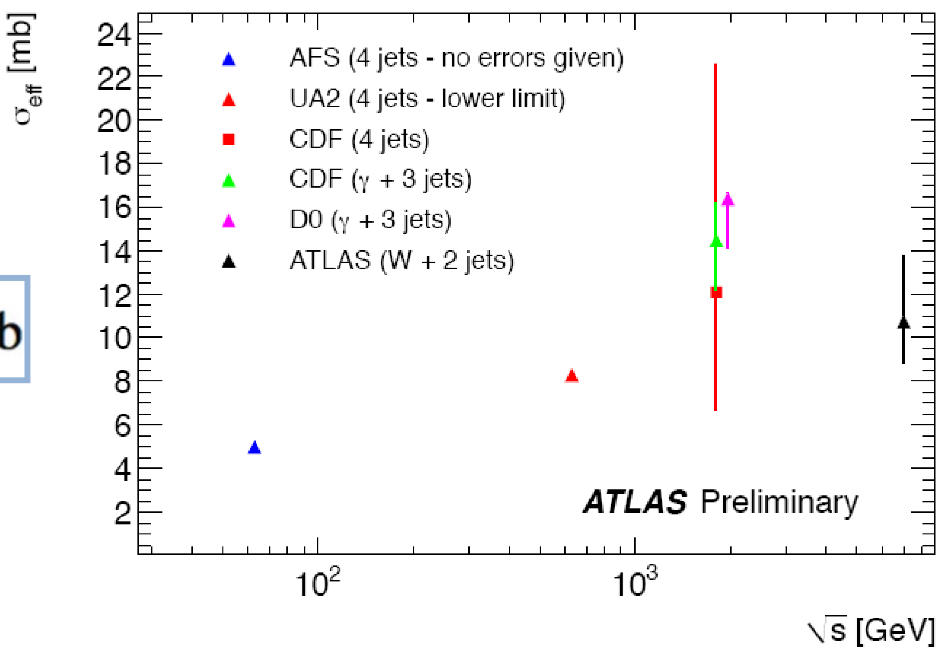
$$f^R_{DP} = 0.16 \pm 0.01\ (\text{stat.}) \pm 0.03\ (\text{sys.})$$

W → lν + 2 jets : σ_{eff}



- extracted component of DPI at the reco level (f^R_{DP}) is a good estimator of the value of f^P_{DP} at parton level
- both predicted and extracted DPI rate decrease as p_T cut is raised

$$\sigma_{\rm eff}(7\,{\rm TeV}) = 11 \pm 1\,({\rm stat.})\,^{+3}_{-2}\,({\rm sys.})\,{\rm mb}$$



- σ_{eff} consistent with Tevatron results
- *s*-dependence not excluded

DPS Prospects: Leptonic FS (4μ)

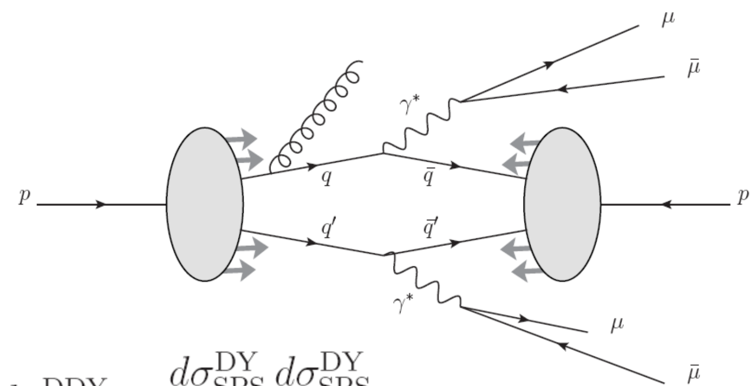
C.H. Kom, A. Kulesza , W.J. Stirling [arXiv:1109.0309]

- DPS expected to peak at low p_T and low Q^2 phase space region → challenge for jet physics

⇒ ***purely leptonic signatures offer a clean probe for underlying scattering mechanisms***

- DPS signal could be dominated by double Drell-Yan production or a quarkonium pair which decay into four leptons
  - DDY → single DY theoretically well understood (standard candle for DPS?)

- sensitivity to different initial state partons: double J/ψ produced predominantly by four gluons, DDY by 2 qqbar pairs (at LO)
  => correlations being probed are different; complementary input to double parton distributions



$$d\sigma^{\rm DDY}_{\rm DPS} = \frac{d\sigma^{\rm DY}_{\rm SPS}\, d\sigma^{\rm DY}_{\rm SPS}}{2\sigma_{\rm eff}}$$

$$d\sigma^{\rm DY}_{\rm SPS} = \sum_{a,b} f_a(x_a,\mu_F) f_b(x_b,\mu_F)\, d\hat{\sigma}^{\rm DY}_{\rm SPS}\, dx_a dx_b$$

Using assumption:

- *longitudinal and transverse components of GPDFs can be factorised*
- *No longitudinal momentum correlations btw partons in the same hadron*

DPS Prospects: Double Drell-Yan

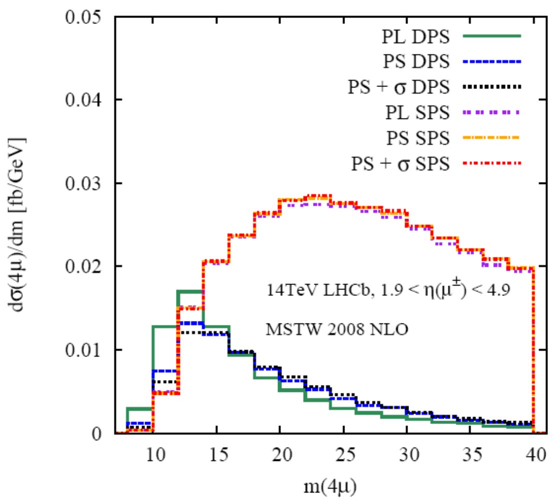
Simulation: $pp \to \gamma^* \gamma^* \to \mu^+ \mu^- \mu^+ \mu^-$

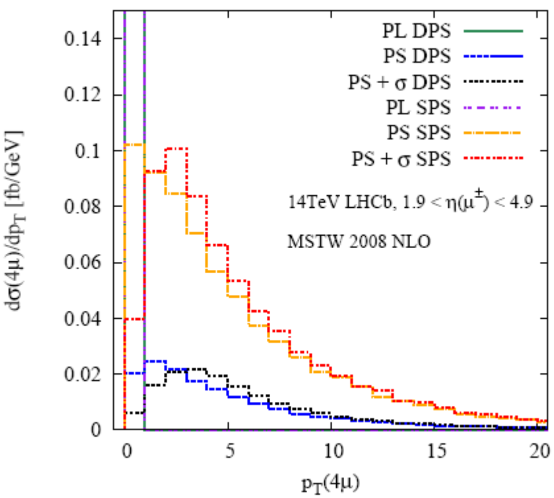
DPS (Herwig++): two hard events generated using the built-in multi-parton scattering model
SPS (Madgraph+Herwig++): single+double resonance diagrams
ISR included, intrinsic p_T smearing of incoming partons applied (DPS+SPS)

- acceptance:
  $1.9 < \eta < 4.9$
  $p_T > 1$ GeV

LHCb-optimized

- good muon identification in the low mass region
- excellent low p_T acceptance, down to 1 GeV





	DPS	SPS
7 TeV	0.08 fb	0.43 fb
14 TeV	0.16 fb	0.68 fb

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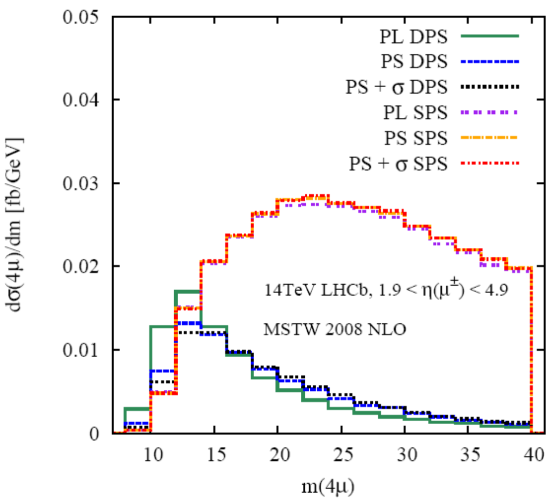
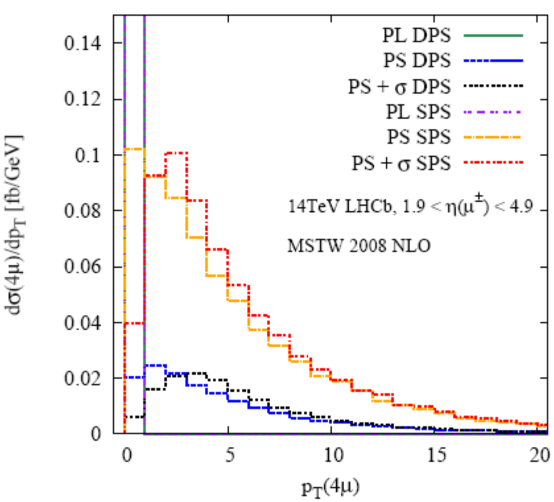




Observing DPS via DDY scattering seems a challenging task!

- *low production rate, no striking kinematical differences observed allowing for efficient DPS selection*
- *more effective to use template method (rather than hard cuts)*

Double J/ψ Production

- contributions from double parton scattering may be significant:

	DPS	SPS
7 TeV	3.16 pb	1.70 pb
14 TeV	7.69 pb	2.62 pb

← theoretical prediction

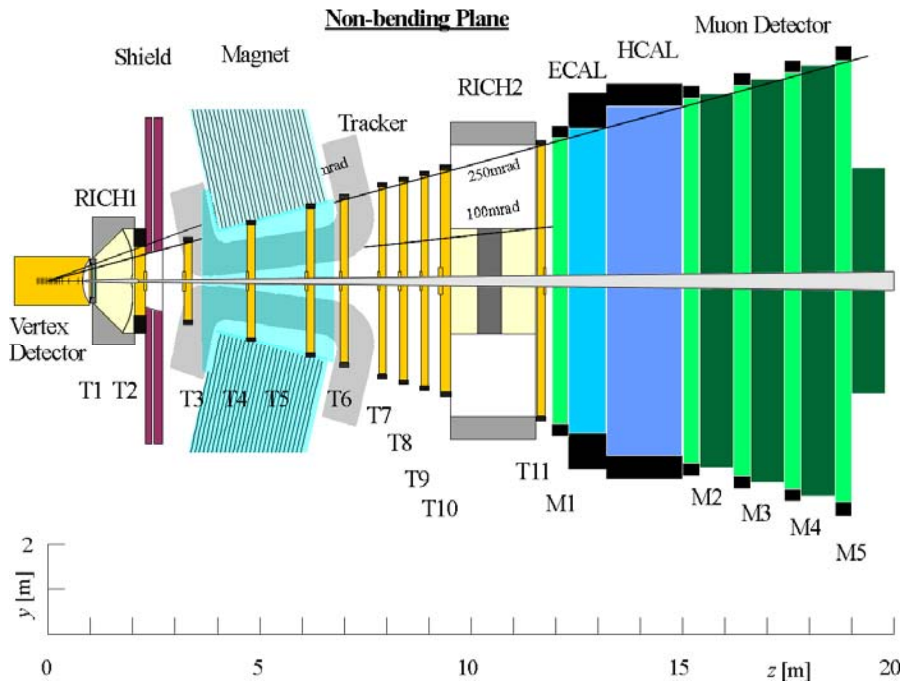
First measurement of charmonia pairs at LHC by LHCb Collaboration

$p_T^{\mu} > 650$ MeV ($\mu+\mu-$ channel)

$3.0 < m_{\mu+\mu-} < 3.2$ GeV

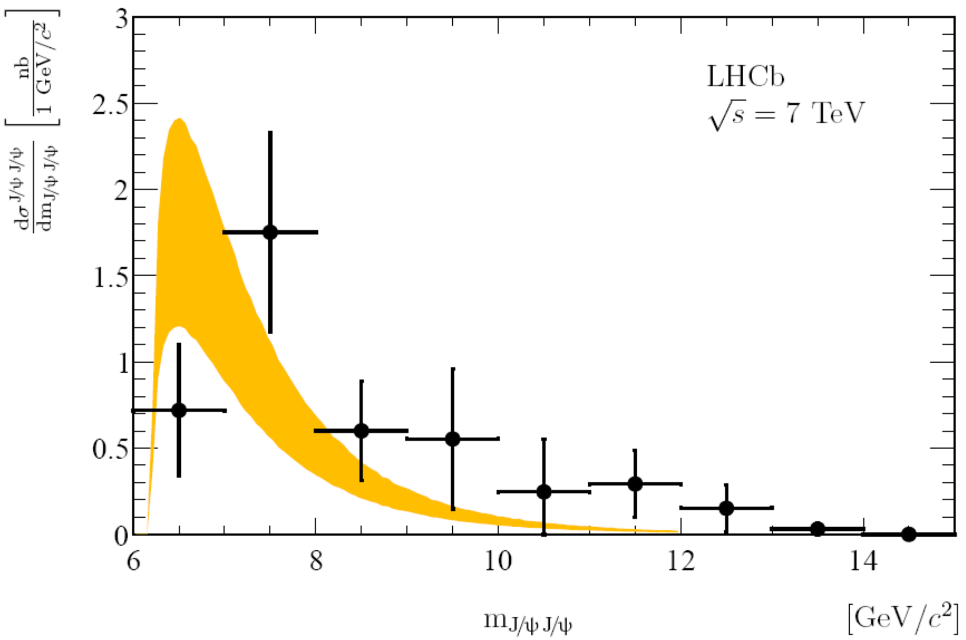
$2 < y^{J/\psi} < 4.5$

$p_T^{J/\psi} < 10$ GeV

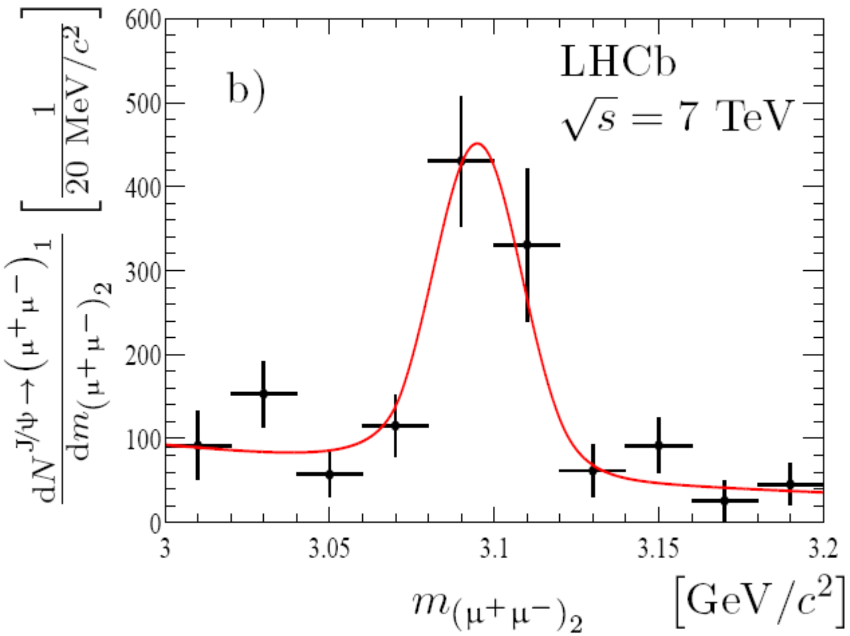


Double J/ψ Production

[arXiv 1109.0963 [hep-ex]]



Corrected event yield: N = 672 +- 129



Fit: *double-sided Crystal Ball function*

- prediction of $\sigma^{J/\psi J/\psi}$ includes direct production and freeddown from ψ(2S), but no DPS
- measured cross-section (6σ excess):

  $\sigma^{J/\psi J/\psi}$ = 5.1 +- 1.0 (stat) +- 1.1 (syst) nb
- reasonable agreement between data and theory (within uncertainties)

→ *contribution from DPS?*

Double J/ψ and DPS

Using σ^{eff} formulation, we can obtain estimation of the contribution from the double parton scattering (single J/ψ production cross-section was measured by LHCb):

$$\sigma_{DPS}^{J/\psi\, J/\psi} = \frac{1}{2}\frac{\sigma_{SPS}^{J/\psi}\,\sigma_{SPS}^{J/\psi}}{\sigma_{eff}} \simeq 2.0 \text{ nb}$$

S.P. Baranov, A.M. Snigirev, N.P. Zotov [Phys. Lett. B 705 (2011) 116–119]

Cross-section through the standard gg→2J/ψ mechanism gives:

$$\sigma_{SPS}^{J/\psi\, J/\psi} = 4.15 \text{ nb}$$

A.V. Berezhnoy, A.K. Likhoded, A.V. Luchnsky, A.A. Novoselov, [arXiv:1101.5881]

Theoretical prediction from both modes : $$\sigma_{SPS}^{J/\psi\, J/\psi} + \sigma_{DPS}^{J/\psi\, J/\psi} = 6.15 \text{ nb}$$

- close to the $\sigma^{J/\psi J/\psi}$ cross-section measured by LHCb ($\sigma^{J/\psi J/\psi}$ = 5.1 +- 1.0 +- 1.1 nb)

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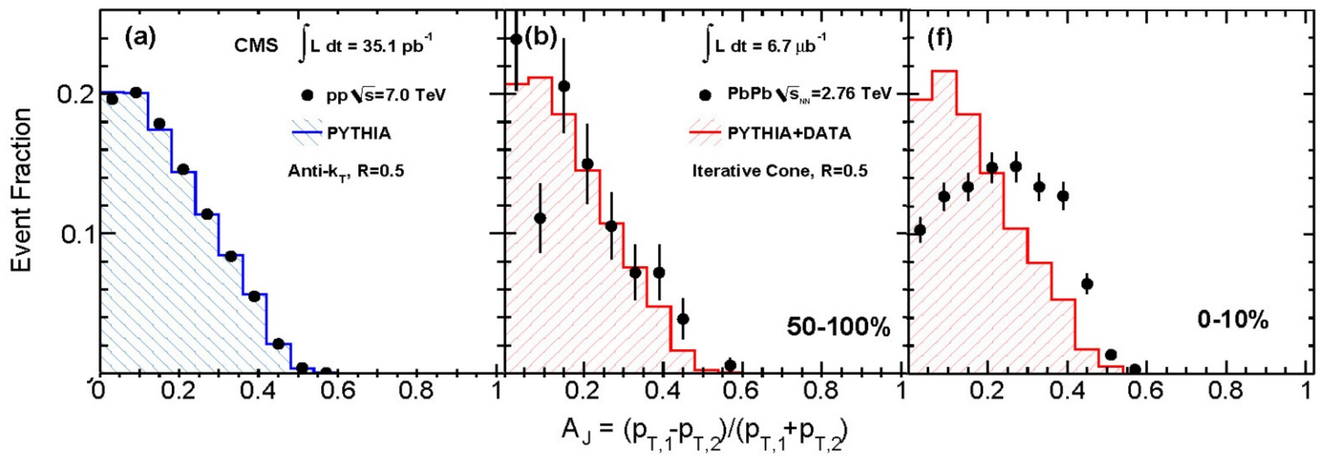
A hint of the evidence to the double parton scattering in the double J/ψ production!

- large th. uncertainties (α_s scale, J/ψ wave function, gluon distr.,…) give factor 2-3

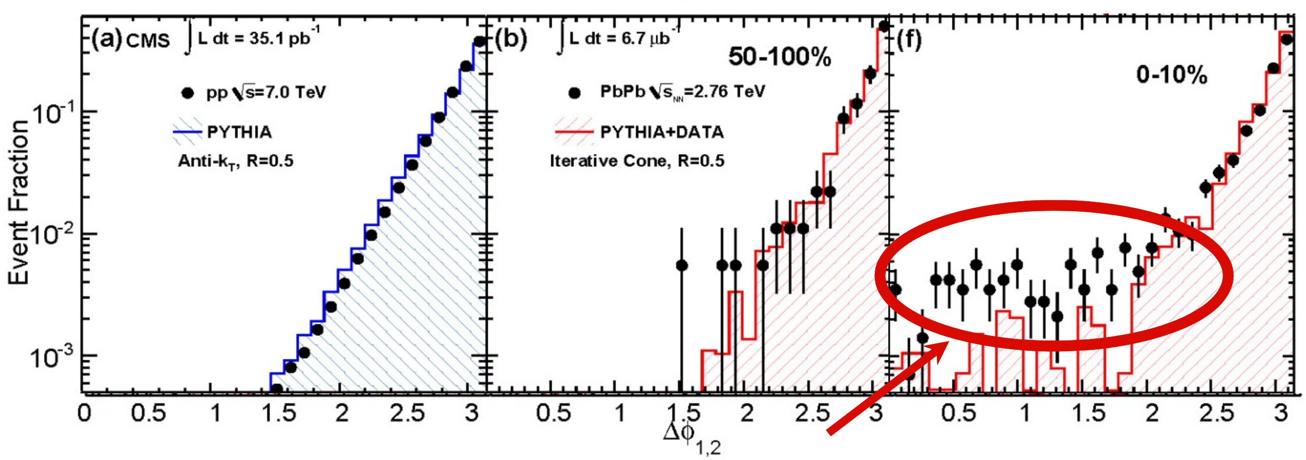
Jet Quenching in PbPb Collisions

pp PbPb, 50 - 100% PbPb 0 - 10%



[arXiv:1102.1957]

Dijets, calorimeters only
Leading p_T>120 GeV/c
Sub-leading p_T>50 GeV/c



Double Parton Scattering

p_T imbalance increasing with centrality

Back-to-back $\Delta\phi \sim \pi$ for all centralities

Conclusions

- huge progress, several recent papers, many other channels not mentioned here being explored (Z+jets, $\gamma\gamma$, …)
- QCD/MPI MC models very successful: unavoidable tools to describe a wide set of observables at hadron colliders
- qualitatively & quantitatively consistent picture from the LHC:

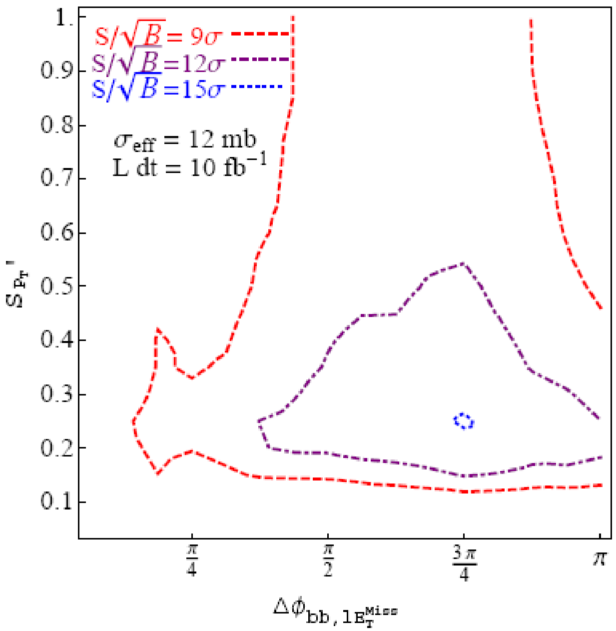
  The LHC is a Multiple Parton Interaction collider

- ATLAS results on σ_{eff} from $W \rightarrow l\nu + 2\ jets$ consistent with results obtained in different channels at the Tevatron
- First double J/ψ cross-section results from LHCb
- DPS observed in PbPb collisions through jet quenching

more results to come!

Backup

Wbb at NLO



Basic acceptance cuts:

$p_{Tb} > 20$ GeV, $|\eta_b| < 2.5$

20 GeV $< p_{T\mu} <$ 50 GeV, $|\eta_\mu| < 2.1$

$E_t^{miss} > 20$ GeV

$\Delta R_{bb} > 0.4$, $\Delta R_{b\mu} > 0.4$

Focus on W decays to muons

Computations done for 7 TeV c.o.m energy