Overview of Soft QCD and diffractive physics at LHC

- Soft QCD processes: inclusive and exclusive measurements;
- Strange mesons/baryons → the MC tuning;
- The inelastic cross section;
- Diffraction (from scintillators to calorimetry);
- A lot of results from ALICE, ATLAS, CMS, LHCb, LXeTP:
  not a comprehensive review;
Inclusive production
Nice agreement between experiments. (MB&UE WG)

| $|h| < 0.5$ | $|h| < 1$ | $|h| < 1$ | $|h| < 0.5$ |

Preliminary 
$\sqrt{s} = 7$ TeV

$n_{ch} \geq 1$, $p_T > 0.5$ GeV, $|\eta| < 0.8$

EPJC68 (2010) 345
Relative increase in $dN_{ch}/d\eta$ but the comparison with MCs is another story...

but...
The forward region $\Rightarrow$ LHCb

$-2.5 < \eta < -2$ or $2 < \eta < 4.5$

$N > 1$ in the $2 < \eta < 4.5$ region

The models (default or tuned) underestimated the charged particle production (as in the central region)

No diffr

At least: 1 track in $2 < \eta < 4.5$ (asimmetry) with $p_t > 1$ GeV/c

Artefact of the event selection for the hard events

Not forward enough?
$$\sqrt{s} = 7 \text{ TeV} \quad p_T > 40 \text{ MeV/c} \quad N_{ch} \geq 1$$

**T2 GEM detector**

(13.5 m from IP)

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**Sherpa by T. Gleisberg et al, JHEP, 0902:007 (2009)**

**Europhysics Lett. 98 (2012) 31002**

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R. Orava, at "Exclusive and diffractive processes in high energy proton-proton and nucleus-nucleus collisions, (2012)"
Event transverse sphericity

\[ S_{xy}^L = \frac{1}{\sum_i P_{Ti}} \sum_i \frac{1}{P_{Ti}} \begin{pmatrix} p_{xi}^2 & p_{xi}p_{yi} \\ p_{xi}p_{yi} & p_{yi}^2 \end{pmatrix} \]

with \( \lambda_1, \lambda_2 \) eigenvalues of the \( S_{xy}^L \) tensor.

\[ S_T = \frac{2\lambda_2}{(\lambda_1 + \lambda_2)} \], with \( \lambda_1, \lambda_2 \) eigenvalues of the \( S_{xy}^L \) tensor.

It's not just a question of rate, charged multiplicity and \( p_T \): events are more spherical, than in MC. Most of the discrepancy comes from hard events.
The search for the ideal tuning \((=\text{ongoing})\) is ongoing:

- The LPCC MB&UE Working Group has suggested several MB&UE “Common Plots” the all the LHC groups can produce and compare with each other.

**Inclusive measurement summary:**
- a wide \(\eta\) interval covered at LHC, the region \(4 < \eta < 5.4\) to be filled by TOTEM T1;
- good agreement between the experiments in the overlapping regions;
- default tunes cannot reproduce the data; few tuning do their job better, although not perfectly (Pythia Z1) yet.
- But what about the single hadron (i.e. different quark) tuning?
Exclusive production
s-quark: soft events, but their modelling is a hard job....

**CMS PAS FSQ-12-014**

- **Pythia8 4C** out for $K/\pi$
- **Pythia D6T** too hard
- **Pythia 6 Z2** out

**CMS preliminary**

- $\langle p_T \rangle$ (GeV/c) vs. $N_{\text{tracks}}$
- $\langle K^+ + K^- \rangle / (\pi^+ + \pi^-)$ vs. $N_{\text{tracks}}$

**ALICE preliminary**

- $\langle K^+ + K^- \rangle / (\pi^+ + \pi^-)$ vs. $\sqrt{s}$ (TeV)
- $\langle p_T \rangle$ (GeV/c) vs. $p_T$ (GeV/c)

**Pyjet**

- ALICE, $pp, \sqrt{s} = 7$ TeV
- ALICE, $pp, \sqrt{s} = 0.5$ TeV
Several tunes were tested, among them PYTHIA Z2, Perugia 2011 and Perugia 0 tunes. These tunes were several times to an order of magnitude below the measured multi-strange spectra and yields (up to a factor 4 for $\Xi^-$, 15 for $\Omega^-$).
At the moment a large abundance of tunings (Z1, Z2, Z2f, D6T, Perugia 0, Perugia 11, ATLAS CSC, C4, 4Cf,...). Most of them reproduce at least few observables, none of them reproduce all the observables.

A big effort ongoing...... A difficult task. Moreover “yes but you have to include diffraction too, that is difficult to be tuned”....so, let’s give a look!

- PYTHIA Z1/Z1C does not describe correctly the $p_T$ distributions of heavy particles (MC too soft);
- PYTHIA Z1 could give problems with LEP data;

See the talk by R. Field @ QCD@LHC, St. Andrews, Scotland, August 25, 2011.

Why tuning is a so difficult task:
- Tuning has to work both for Minimum Bias (MB) and Underlying Events (UE);
- A lot of different mechanisms at work;
- It’s easy to modify a given parameter to reproduce an observable; it’s difficult to find a single tuning for LEP, CDF, LHC data and for the different LHC energies....
..and now diffraction!

Single diffraction
- SD
- \( \Phi \)
- \( \eta \)
- LRG

Single diffraction
- SD
- \( \Phi \)
- \( \eta \)
- LRG

Double diffraction
- DD
- \( \Phi \)
- \( \eta \)
- LRG

Central diffraction
- CD(DPE)
- \( \Phi \)
- \( \eta \)
- LRG

DiJet Diffraction
- \( \Phi \)
- \( \eta \)
- LRG

W,Z Diffraction
- \( \Phi \)
- \( \eta \)
- LRG

probes the quark content of the Pomeron
Diffractive processes are a relevant fraction of the total cross section $\sigma_{\text{tot}} \rightarrow$ their understanding is mandatory for a full MB and UE modeling

- Going from experimental observables to physics quantities requires MC $\rightarrow$ results often model dependent;
- Diffraction physics requires low pile up runs;
- Experimental challenge: most of the proton excitation remains into the beam pipe;
- Smooth transition from DD to Non Diffractive (ND);
- Small contribution from CD (DPE): modelling not trivial;

Two techniques: - beam proton tagging or (requires roman pots, limited $\eta$)
- large rapidity GAP (widely used)
The INEL cross section
MBTS (Minimum Bias Trigger Scintillator) ±3.6 m from the IP, 2.1 < |η| < 3.8

intact p: η = 8.85 (± 7 TeV)
X system: η_X < 3.8
→ Δη ≤ 12.2

ξ ≈ e^{-Δη} > 5 \times 10^{-6}
ξ = \frac{M_X^2}{s} \rightarrow M_X > 15.7 \text{ GeV}

The first commandment: constrain the diffraction

Single sided event ratio \( R_{ss} = \frac{N_{SS}}{All} \)
MC generators predict < 1% of the ND process pass the single-sided event selection, whereas 27–41% of the SD and DD processes pass the single-sided selection, sensitive to the relative fraction of diffractive events \( R_{ss} = \frac{N_{SS}}{All} \).

\[ R_{ss} = (10.02 \pm 0.03 \text{(stat)} \pm 0.1 \text{(sys.)})\% \]

\( f_D = (\sigma_{SD} + \sigma_{DD} + \sigma_{CD}) / \sigma_{inel} = (26.9 \pm 2.5 \% \)
MC rescaling: Pythia 8 + the Donnachie and Landshoff tuning (DL) is the ATLAS Ref. model: $F_D^{\text{(DL)}}=26.9\%$

Beam gas events

$$\sigma_{\text{inel}} (\xi > 5 \cdot 10^{-6}) = \frac{(N-N_{\text{back}}) \cdot (1-f_{\xi<5\cdot10^{-6}})}{\varepsilon_{\text{trig}} \cdot L \cdot \varepsilon_{\text{sel}}} = (60.3 \pm 0.05(\text{stat}) \pm 2.1(\text{lumi})) \text{ mb}$$

Going from $\xi > 5 \cdot 10^{-6}$ to the full range $\Rightarrow \varepsilon (\xi > 5 \cdot 10^{-6}) = (87\pm10)\%$, ranging from - 79% (Ryskin et al., EPJ C71(2011) 1617) - 96% (Phojet)

Central value by Donnachie and Landshoff (DL), $d\sigma_{SD}/d\xi \sim 1/\xi^{1+\varepsilon}$, $\alpha'=0.35\text{GeV/c}$ and $\varepsilon=0.085$, $\alpha(t) = \alpha(0)+\alpha't$.

$$\sigma_{\text{inel}} = (69.1 \pm 2.4(\text{stat}) \pm 6.9(\text{lumi})) \text{ mb}$$
Consider the trigger made of V0A and VOC (V0-and) \( \rightarrow \sigma \) by VdM scan. Then V0-and/inel by SD and DD tuned MC \( \varepsilon = (0.745 \pm 0.010) \) @ 7 TeV

Preliminary ALICE result : \( \sigma = (72.7 \pm 1.1 \) (model) \( \pm 5.1 \) (lumi)) mb @ 7 TeV

\( \sigma = (69.1 \pm 2.4 \) (stat) \( \pm 6.9 \) (model) \) mb (1)

\( \sigma = (64.5 \pm 1.1 \) (sys) \( \pm 1.5 \) (model) \( \pm 2.6 \) (lumi)) mb (2)

\( \sigma = (73.5 \pm 0.5 \) (stat) \( \pm 1.8 \) (sys) \) mb (3)

ATLAS-CMS/ALICE results agree if the same model is used to extract \( \varepsilon \) (ATLAS use the DL model, ALICE model has a \( 1/M_x \) steeper scaling)

\[ \Rightarrow \sigma_{\text{INEL}} \sim (70 \pm 5) \text{ mb at } \sqrt{s} = 7 \text{ TeV} \]
Measure $N_{\text{1 arm trigger}} / N_{\text{2 arm trigger}}$

$\varepsilon_{\text{SD}} \rightarrow \text{Prob. SD triggered as 1 arm, 2 arm}$

$\varepsilon_{\text{NSD}} \rightarrow \text{Prob. NSD triggered as 1 arm, 2 arm}$

Vary $\sigma_{\text{SD}}/\sigma_{\text{NSD}}$ to reproduce exp data

$\rightarrow$ SD fraction fixed

Phytia overestimates
PHOJET underestimates DD

Events with $\Delta\eta > 3$ $\rightarrow$ DD

Can be used to tune
DD fraction in MC
(~8% at 7 TeV) $\rightarrow$ DD fraction fixed

$\sqrt{s} = 0.9$ TeV

$\sigma_{\text{SD}}/\sigma_{\text{Inel}} = 0.202 \pm 0.034 \ (\text{sys})$

$\sigma_{\text{DD}}/\sigma_{\text{Inel}} = 0.113 \pm 0.029 \ (\text{sys})$

$\sqrt{s} = 2.76$ TeV

$\sigma_{\text{SD}}/\sigma_{\text{Inel}} = 0.187 \pm 0.054\ (\text{sys})$

$\sigma_{\text{DD}}/\sigma_{\text{Inel}} = 0.125 \pm 0.052\ (\text{sys})$

$\sqrt{s} = 7$ TeV

$\sigma_{\text{SD}}/\sigma_{\text{Inel}} = 0.201 \pm 0.039 \ (\text{sys})$

$\sigma_{\text{DD}}/\sigma_{\text{Inel}} = 0.122 \pm 0.036\ (\text{sys})$
Understanding diffraction....
...the advantage of the calorimetry.
PYTHIA D6T overestimates SD; spectrum too soft. PHOJET underestimates SD, but agrees in the higher part
**Rapidity gap cross section**

Analysis based on: EMCAL, Fcal, $\eta$ region considered $-4.9 < \eta < 4.9$.
An $\eta$ slice is active when (track with $P_t > 200$ MeV OR at least 1 calorimeter cell fired)

Forward gap: starting from the $\eta$ edge($\pm 4.9$), select the largest consecutive set of empty slices.

Intact p ($\sqrt{s} = 7$ TeV) $\rightarrow$ $\eta = 8.9$

$\Delta \eta_F = 3$

$\Delta \eta = 4 + \Delta \eta_F$

$\Delta \eta = -\ln \xi$

$ND \rightarrow \Delta \eta_F \sim 0$

Diffractive events: large $\Delta \eta_F$

Pythia 8: agreement at low and high $D_F$

PHOJET: agreement at intermediate $D_F$

PYTHIA $s_{IN}$ overall overestimate or just right. DD decreases in PHOJET?

ND dominates this region, due to fluctuations: $D_F$ decreases too much at large $D_F$ in PHOJET, rise not reproduced (SD+DD) dynamics.
\[ \Delta \eta \sim -\ln \xi = - \ln M_x^2/s \]

More on \( \sigma_{\text{inel}} \)

Previous measurement from MBST

Comparing the cross section at \( \xi > 8 \cdot 10^{-6} \) and at \( \xi > 2 \cdot 10^{-8} \)

ATLAS-TOTEM \((14.5 \pm 2.0) \text{mb}\)

Pythia \(~ 6 \text{ mb}\)

KMR (Ryskin) \(~ 12 \text{ mb}\)

The contribution to the \( \sigma_{\text{inel}} \) from \( \xi < 8 \cdot 10^{-6} \) larger than predicted by most models
Diffractive events with a hard parton-parton scattering

Search for diffraction with a hard scale (signature: no hadronic activity in a wide $\eta$ range)

Study of diffractive structure function:

$$\sigma(pp \to ppX) \sim F_{jj} \times F_{jj}^D \times \sigma(ab \to jj) \rightarrow \sigma_{SD}/\sigma_{ND} = \frac{F_{jj}^D}{F_{jj}} \text{ known}$$

Trigger on $E_t > 6$ GeV. Jets with $P_t > 20$ GeV and $-4.4 < \eta < 4.4$. \( L = 2.7 \text{ nb}^{-1} \)

Particle flow object (particle candidates obtained by combining tracking + calorimetry with $\eta_{\text{min}} > 3$, $\eta_{\text{max}} < 3$) \rightarrow gap of $> 1.9 \eta$ unit in HF,

results presented as a function of

$$\Xi^\pm = C \Sigma (Ei \pm pzi) / \sqrt{s} \quad 0.5*(\xi^- + \xi^+) \sim \xi = M^2 x/s, \ C \sim 1.45 \text{ (from MC)}$$
**Diffraction at HERA**

Two step process: Pomeron emission + Hard scattering
\[ \sigma \sim F_{jj} \times F_{jj}^D \times \sigma(ab \rightarrow jj) \] (hard scattering)

**Diffraction at CDF**

Factorization broken: soft interaction/rescattering
the rapidity gap: \( \sigma \propto \langle s^2 \rangle \)

At LHC RGS prediction 5-25 %

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*PRL 84 5043 (2000)*
PYTHIA/POMPYT:
Same diffractive parton distribution, but different pomeron flux

- MC not including diffraction (PYTHIA 8, Z2) cannot reproduce data at low $\xi$;
- Pythia 8 (SD + DD) is not enough; same dPDF than POMPYT/POMWIG, but different IP flux;
- POMPYT/POMPYT (SD) ( ) needed at low x, but their normalization higher at low $\xi$;
- RGS(Rapity Gap Survival):

Data: includes p excited into low mass undetected in the forward region;
POMPYT: does not include RGS, but the dPDF includes a p dissociative contribution;
RGS upper limit: data/POMPYT = (0.21±0.07)
One central and isolated lepton ($\eta < 1.4$) with $p_T > 25$ GeV, pt miss > 30 GeV: 32,000 ev
HF+ or HF- with no energy (1.9 gap): ~ 300 ev $\rightarrow$ ~ 1%

Select events with no energy in one side:
Lepton and the gap in the same hemisphere $\rightarrow$ $\eta_{\text{lept}} > 0$
Lepton and the gap in opposite hemisphere $\rightarrow$ $\eta_{\text{lept}} < 0$

Asimmetry (not reproduced by Pythia):
dPDF smaller $x$ wrt PDF $\rightarrow$ produced W boosted in the direction of the parton with the largest $x$ $\rightarrow$ opposite to the gap

Best fit diffraction component:
(50.0 ± 9.3 (stat.) ± 4.2 (syst.)) %

W with LRG fraction: (1.46 ± 0.09(stat)±0.38(syst.))%
**Ultra peripheral Collisions (UPC):** ongoing analysis for heavy meson production in Pb-Pb collisions ($J/\Psi, \Upsilon$): access to the nuclear gluon structure function, $\sigma_{J/\Psi, \Upsilon} \propto |x \cdot g(x, q^2)|^2$

$J/\Psi, \Upsilon$ production allows the measurement of the gluon shadowing in the nucleus
Conclusions

- Impressive amount of work from the LHC experiments on soft QCD/diffractive physics;

- In general good agreement between experimental results;

- A MC tuning, reproducing simultaneously all the observables still missing. Strange hadron production modeling requires more work;

- Inelastic cross section measured: \((70 \pm 5)\) mb at \(\sqrt{s} = 7\) TeV: results are model dependent;

- Diffraction process study shows significant advance: few of them nicely constrained (SD \(\sim\) 20\%, DD \(\sim\) 10-15\%), CD still missing;

- Calorimetry is performing nicely in the forward physics, providing exciting results;

- A lot of new results coming;
ALICE-ATLAS UE

"Transverse" Charged Particle Density: $dN/d\eta d\phi$

RDF Preliminary
Tune Z1 generator level

7 TeV Charged Particles ($|\eta| < 0.8$, $PT > 0.5$ GeV/c)

PTmax (GeV/c)

"Transverse" Charged PTsum Density: $dPT/d\eta d\phi$

RDF Preliminary
Tune Z1 generator level

900 GeV Charged Particles ($|\eta| < 0.8$, $PT > 0.5$ GeV/c)

PTmax (GeV/c)