Brief overview of theory progress in $W + b$ jets and $Z + b$ jets

Towards a more coherent interpretation of experimental measurements

Laura Reina

ATLAS workshop on $H \to b\bar{b}$ and flavor tagging

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Relevance of $V + b$ jets ($V = W^{\pm}, Z$):

- Main **background** to several important SM and BSM signatures:
  - WH/ZH associated production, $H \to b\bar{b}$;
  - single-top production;
  - several BSM signatures (with $l^{\pm}$, $\not{E}_T$, b jets, light jets).
- Direct access to b **parton density** (true also for $\gamma + b$ jets),
  - intrinsic QCD relevance;
  - impact on $H + b$-jet searches, ...
- **testing ground** for other complex processes involving b jets (ex.: $t\bar{t} + b$ jets).

Main ideas for this talk:

- $W/Z + b$ jets are **multi-scale processes** ($m_b \gg \Lambda_{QCD}$, $m_b \ll M_{W/Z}$).
- Need to control **sensitivity to $\mathbf{m_b}$ in theoretical predictions**
  $\hookrightarrow$ b quarks/jets have a well defined exp. identity.
- **$\mathbf{m_b}$ effects** present at all levels
  $\hookrightarrow$ hard matrix element, parton shower, PDF, ...
- Develop good understanding of what is involved in theory predictions.
- Improve **estimate of theoretical accuracy**.

A quick synopsis: W vs. Z, and $1b$ vs. $2b$ jets

$V + 2b$ jets:

only via the tree-level processes ($n_{lf} = 4 \to$ 4FS, $m_b \neq 0$)

- $\to\ q\bar{q}' \to Wb\bar{b}$
- $\to\ q\bar{q}, gg \to Zb\bar{b}/\gamma b\bar{b}$

and corresponding higher-order corrections.

$V + 1b$ jet:

still via the tree-level processes ($n_{lf} = 4 \to$ 4FS, $m_b \neq 0$)

- $\to\ q\bar{q}' \to Wb\bar{b}$
- $\to\ q\bar{q}, gg \to Zb\bar{b}/\gamma b\bar{b}$

but also ($n_{lf} = 5 \to$ 5NS, $m_b = 0$, only kept as IR regulator),

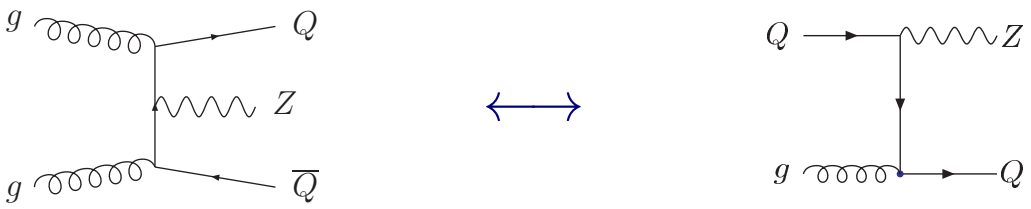
- $\to\ b\bar{q} \to Wb + q'$
- $\to\ bg \to Zb/\gamma b$

and corresponding higher-order corrections.

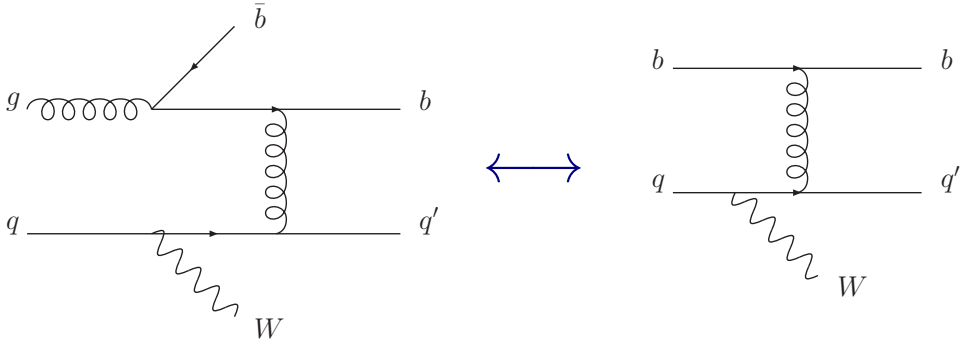
4FS vs 5FS: a technical means of "improving" the perturbative expansion.

Observe that:

- $bg \to Zb/\gamma b$ is related to $gg \to Zb\bar{b}/\gamma b\bar{b}$,



- $bg \to Wb + q'$ is related to $qg \to Wb\bar{b} + q'$,



by defining a purely perturbative b-quark density (from $g \to b\bar{b}$), e.g.

$$b(x,\mu) = \frac{\alpha_s}{2\pi} \ln \frac{\boldsymbol{\mu^2}}{\mathbf{m_b^2}} \int_x^1 \frac{dz}{z} P_{qg}(z) g\left(\frac{x}{z}, \mu\right) + \cdots$$

[expansion at first order of the RGE evolved $b(x,\mu)$]

Where:

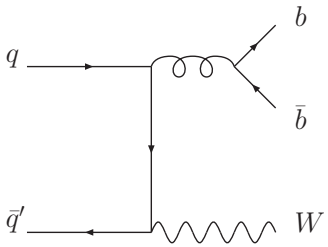
- **Potentially large logarithmic corrections** arise from phase-space integration of untagged b quark.
- They can be **resummed** using RG techniques into $b(x, \mu)$: **5FS often brings stability to total cross sections**.
- Non-logarithmic m_b dependence and kinematic information partially missed in 5FS: **4FS more reliable for distributions**.
- Possible to **combine both approaches** (4FS ad 5FS) using matching techniques, [for $H + b$-jets see: Bonvini et al., arXiv:1508.05288 (EFT); Forte et al., arXiv:1508.01529, arXiv:1607.00389 (FONNL)].

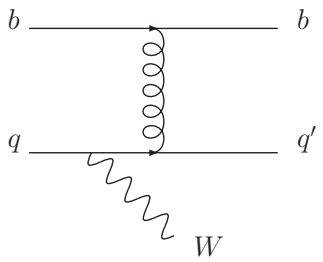
And yet:

- **4FS and 5FS** calculations **need to be interfaced with parton-shower** (PS) event generators, including NLO QCD corrections.
- Can 5FS+PS be implemented without loosing m_b information?
  - how to reconcile the kinematic of a massive b quark, and $m_b \neq 0$ in the PS, with $m_b = 0$ in the hard scattering?
  - Is $m_b = 0$ required by b initiated processes?
  - Is an initial-state massive b consistent with available b PDF?
- Are there **other $\mathbf{m_b}$-related effects** that we should also investigate (ex: final state enhanced $g \to b\bar{b}$ splitting)?

$W + 1b$ jet vs. $W + 2b$ jets

One or two LO processes, depending on choice of 4FS vs 5FS:





$+ \quad O(\alpha_s)$ corrections

Correspondently, at NLO:

1. $q\bar{q}' \to Wb\bar{b}$ at tree level and one loop ($m_b \neq 0$)
2. $q\bar{q}' \to Wb\bar{b}g$ at tree level ($m_b \neq 0$)
3. $bq \to Wbq'$ at tree level and one loop ($m_b = 0$)
4. $bq \to Wbq'g$ and $bg \to Wbq'\bar{q}$ at tree level ($m_b = 0$)
5. $gq \to Wb\bar{b}q'$ at tree level ($m_b \neq 0$) $\to$ avoiding double counting

- ▷ $W + 2b$ jets: processes $1 + 2 + 5$
- ▷ $W + 2$ jets with at least one b jet: processes $1 + 2 + 5$ (4FS) or $1 + \cdots + 5$ (5FS).

↪ **In the case of $W + 1b$ the 5FS calculation include the 4FS one.**

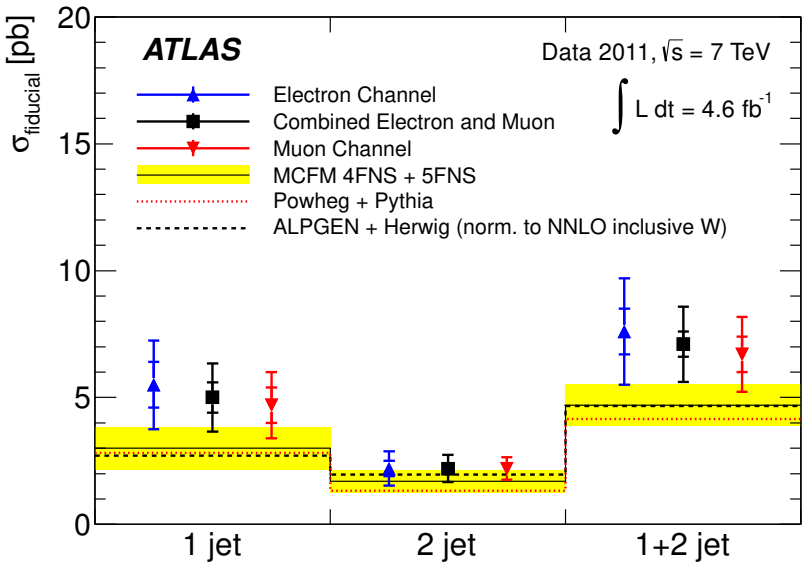
NLO QCD studies vs. experimental measurements

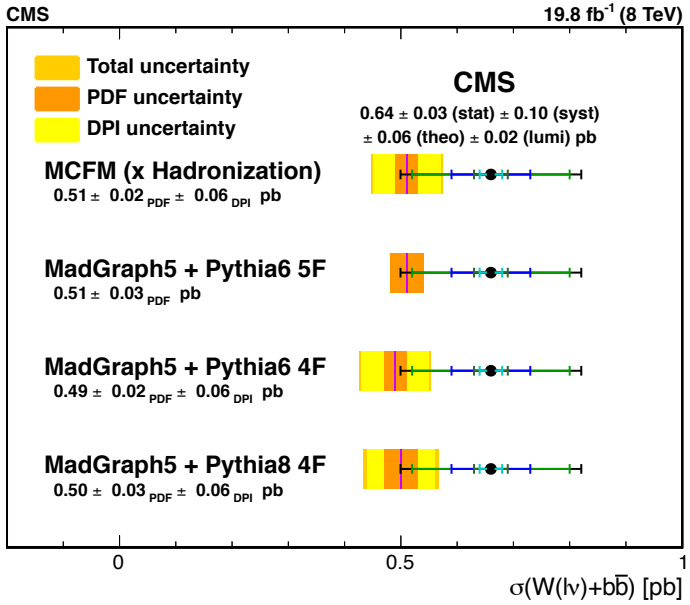
- $W + 2b$ jets:
  - Febres Cordero, L.R., Wackeroth, hep-ph/0606102, arXiv:0906.1923 (4FS)
  - Badger, Campbell, Ellis, arXiv:1011.6647 (4FS, $W \to l\nu$) $\to$ MCFM
  - Oleari, L.R., arXiv.1105.4488 (4FS) $\to$ POWHEG-BOX
  - Frederix, et al., arXiv:1106.6019 (4FS) $\to$ MG5aMC@NLO
  - the CMS collaboration, arXiv:1312.6608, arXiv:1608.07561.

- $W + 2b +$ jet:
  - L.R., Schutzmeier, arXiv:1110.4438 (4FS, one-loop only)
  - Luisoni, Oleari, Tramontano, arXiv:1502.01213 (4FS) $\to$ POWHEG-BOX

- $W + 2$ jets with at least one b jet:
  - Campbell, et al., arXiv:0809.3003, arXiv:1107.3714 (5FS) $\to$ MCFM
  - the CDF collaboration, arXiv:0909.1505,
  - the D0 collaboration, arXiv:1210.0627
  - the ATLAS collaboration, arXiv:1109.1470, arXiv:1302.2929.

Comparison with ATLAS and CMS

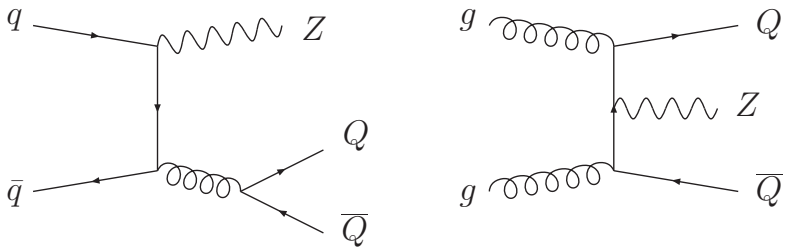




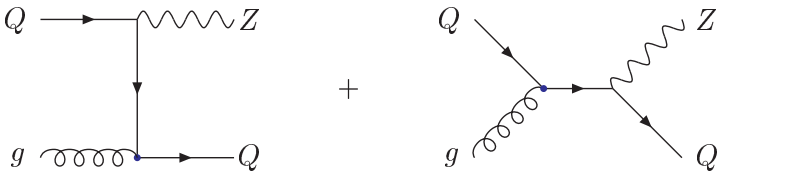
- ATLAS and CMS **complementary measurements**: $W + b + j$ vs. $W + 2b$.
- Difficult to interpret CMS comparison with theory, NLO QCD vs. LO+PS (normalized).
- Much **more thorough study of theoretical systematic needed** (scales, PDF, m_b, DPI, PS effects; multiple jet samples; ...)
- Useful to test different tools (ex.: $W + 2b$ also available in POWHEG-BOX).

$Z + 2b$ jets vs. $Z + 1b$ jets

LO processes, depend on choice of 4FS vs 5FS:



$+ \quad O(\alpha_s)$ corrections



$+ \quad O(\alpha_s)$ corrections

Correspondently, at NLO:

1. $q\bar{q}, gg \to Zb\bar{b}$ at tree level and one loop (with $m_b \neq 0$);
2. $q\bar{q}, gg \to Zb\bar{b} + g$ and $gq(g\bar{q}) \to Zb\bar{b} + q(\bar{q})$ (with $m_b \neq 0$).
3. $bg \to Zb$ at tree level and one loop (with $m_b = 0$);
4. $bg \to Zb + g$, $bq \to Zb + q$ (with $m_b = 0$);

$Z + 2b$ jets: processes $1 + 2$

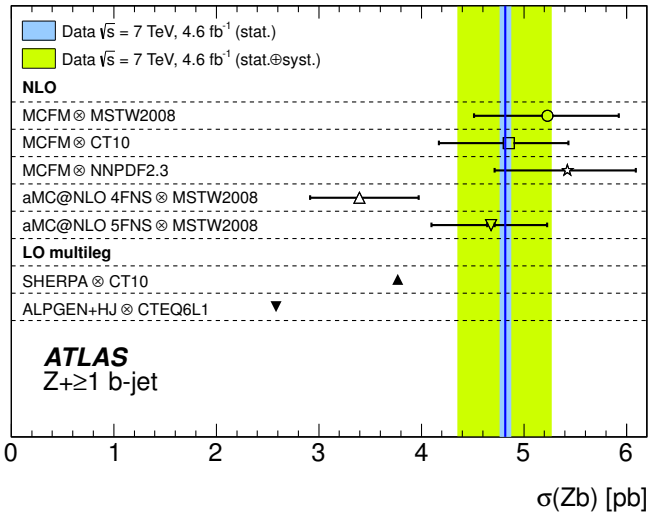
$Z + 1b$ jet: processes $3 + 4 + (1 + 2)_{LO}$ (5FS) or $(1 + 2)_{NLO}$ (4FS)

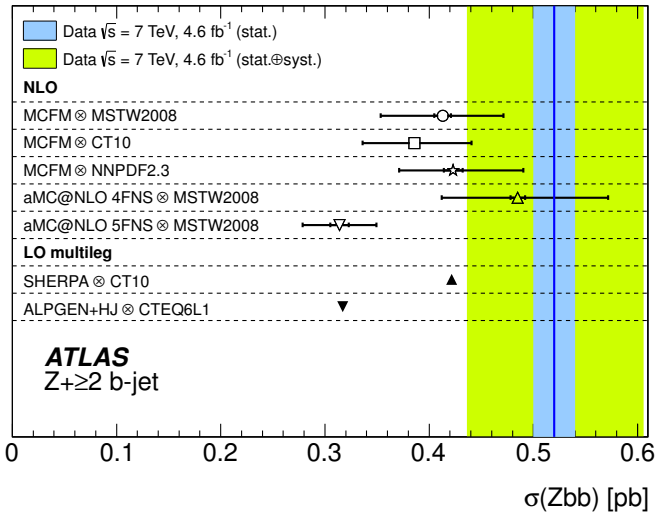
NLO QCD studies vs. experimental measurements

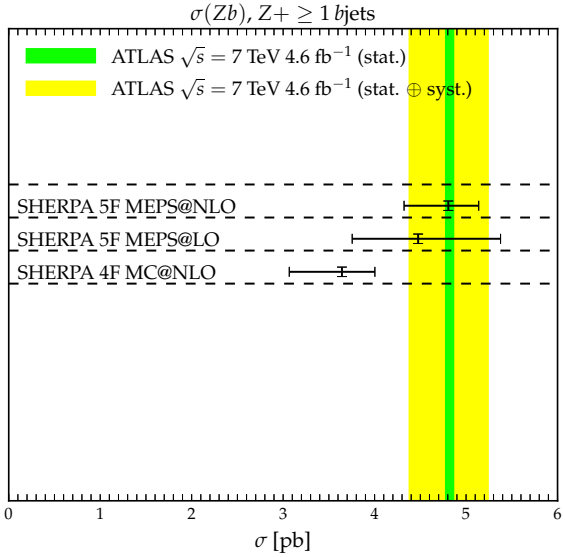
- $Z + 2b$ jets:
  - Febres Cordero, L.R., Wackeroth, arXiv:0806.0808, arXiv:0906.1923 (4FS)
  - Frederix, et al., arXiv:1106.6019 (4FS) $\rightarrow$ MG5aMC@NLO
  - Krauss, Napoletano, Schumann arXiv:1612.04640 (4FS) $\rightarrow$ OL+SHERPA
  - the CMS collaboration, arXiv:1310.1349

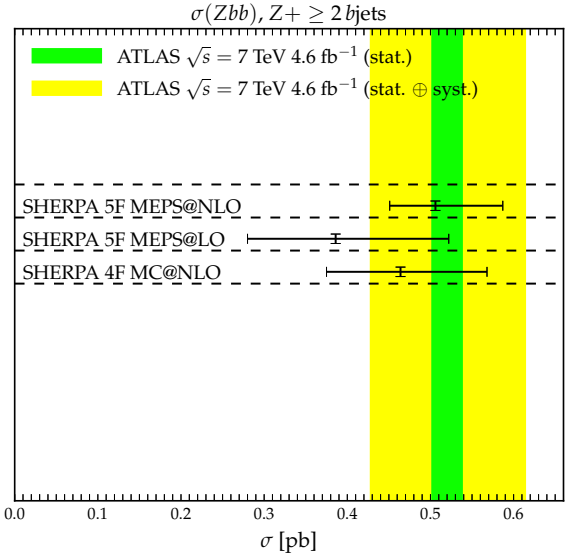
- $Z + 1b$ jet, $Z + 2$ jets with at least one b jet:
  - Campbell, Ellis, Maltoni, Willenbrock, hep-ph/0312024 (5FS) $\rightarrow$ MCFM
  - Campbell, Ellis, Maltoni, Willenbrock, hep-ph/0510362 (5FS) $\rightarrow$ MCFM
  - Frederix, et al., arXiv:1106.6019 (5FS) $\rightarrow$ MG5aMC@NLO
  - Krauss, Napoletano, Schumann arXiv:1612.04640 (5FS) $\rightarrow$ OL+SHERPA
  - the CDF collaboration, hep-ex/0812.4458,
  - the D0 collaboration, arXiv:1301.2233
  - the ATLAS collaboration, arXiv:1109.1403
  - the CMS collaboration, arXiv:1402.1521, arXiv:1611.06507

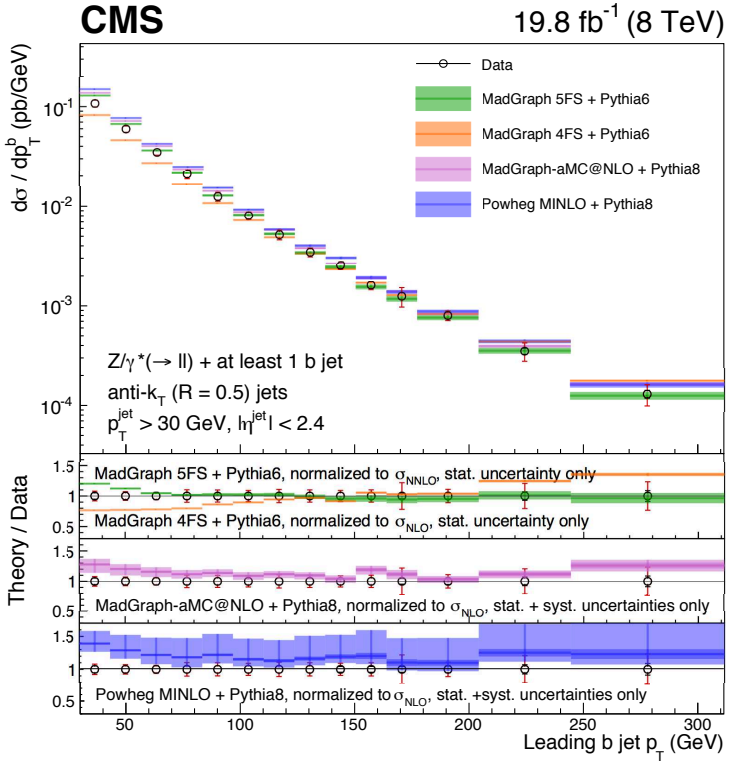
Comparison with ATLAS and CMS

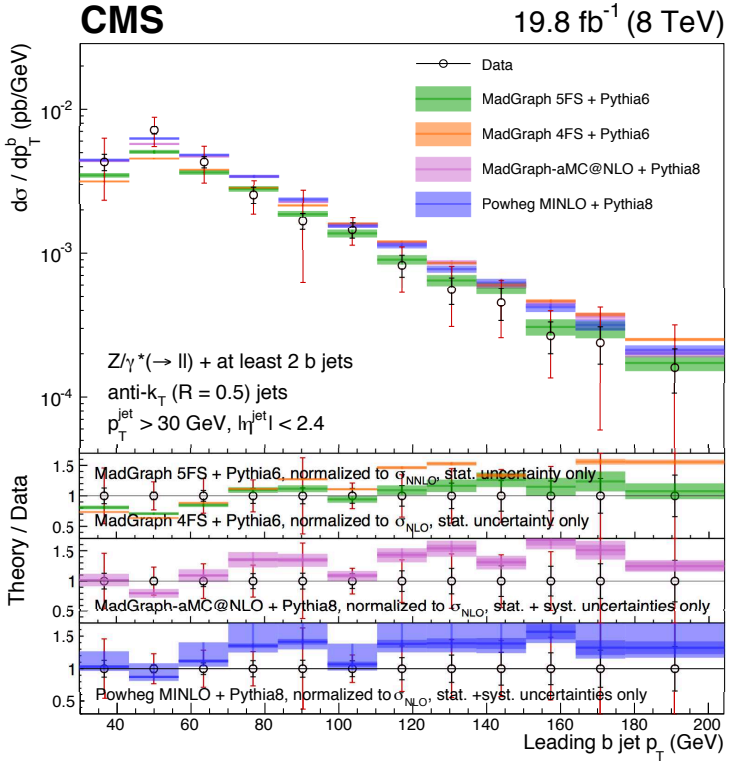












- ATLAS and CMS **both measured $\mathbf{Z + 1b}$** and **$\mathbf{Z + 2b}$** (including distributions: p_T^b, p_T^Z, η^b, H_T, $m_{b\bar{b}}$, $m_{b\bar{b}Z}$, R_{bZ}, $R_{b\bar{b}}$, ...)
- **Interesting comparison** 4FS vs. 5FS (+PS).
- Much more **thorough study of theoretical systematic needed**.
- Good candidate to study m_b effects in 5FS (all levels).

Outlook

- We seem to be converging towards a more definite understanding of $V + b$ jets at hadron collider.
  $\hookrightarrow$ For a **review aimed at interpretation of exp. measurements**:
  [Febres Cordero, L.R., arXiv:1504.07177]
- Experimental precision soon better than theoretical accuracy.
- **W/Z + b** jets now **available** (4FS/5FS) **in several NLO PS event generators**:
  $\hookrightarrow$ $V + 1b$ can be tricky to properly account for m_b effects. state.
  $\hookrightarrow$ Other m_b dependent PS effects need to be studied.
- **Measurements** could be **tailored to specific theoretical issues**: isolate samples with definite number of light and b jets, distinguish b and $(b\bar{b})$ in jets, distributions, ...
- **More systematic estimate of theoretical accuracy** needed
  (scales, PDF, m_b, DPI, PS effects; ...)