b jets at 100 TeV

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PRELIMINARY RESULTS for DISCUSSION for the REPORT

FCC Workshop - QCD, EW and tools at 100 TeV
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$\sigma_{TOT}(pp \to X)$ as a function of $(\sqrt{s})$ for different processes

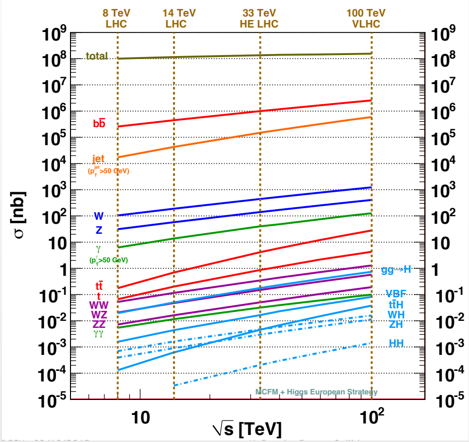


figure from K. Desch, 2015

$\sigma_{b\bar{b}}$ more than 1000 larger than σ_W over the whole $\sqrt{s}$ range [7 TeV, 100 TeV].

Some motivations for studying B-hadrons and b-jets at 100 TeV

$*$ Due to the enormous cross-section, $b + X$ and $b\bar{b} + X$ hadroproduction at 100 TeV allows for precise tests of QCD.

$*$ This allows to study rare decays of B-mesons and baryons, providing stringent tests on the Standard Model.

$*$ b-jets are important background for SM H, Z production and decay in $b\bar{b}$ (so far the direct experimental observation of Higgs decay to $b\bar{b}$ with high statistical significance is still missing).

$*$ b-jets are a background for BSM searches (e.g. $\chi\chi \to b\bar{b}$)

$*$ Production of heavy-quarks at ultra high-energies plays a role in astroparticle physics.

High-energy cosmic ray spectrum

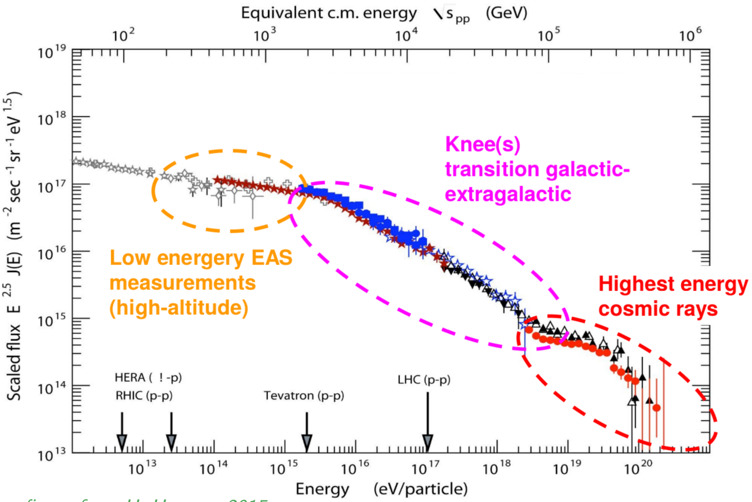


figure from H. Haungs, 2015

∗ CR primary energies extend well beyond 100 TeV (GZK cutoff $\sim 300 - 400\,TeV$)

∗ present uncertainties on the galactic-to-extragalactic transition and the CR composition at UHE could be (at least partially) addressed by reducing our theoretical uncertainties on hadroproduction at 100 TeV.

Heavy-quark hadroproduction: relative importance of different species

At the present run of LHC, expected cross-sections amount to:

$$\sigma(pp \to t\bar{t}, m_t^{pole} = 172.5 \text{ GeV}) \sim 716 \text{ pb} \quad \text{at} \quad E_{CM} = 13 \text{ TeV}$$

$$\sigma(pp \to b\bar{b}, m_b^{\bar{M}\bar{S}}(m_b) = 4.2 \text{ GeV}) \sim 628.4\ \mu\text{b} \quad \text{at} \quad E_{CM} = 13 \text{ TeV}$$

$$\sigma(pp \to c\bar{c}, m_c^{\bar{M}S}(m_c) = 1.27 \text{ GeV})) \sim 13.4 \text{ mb} \quad \text{at} \quad E_{CM} = 13 \text{ TeV}$$

$$\sigma(c\bar{c}) = 21.3 * \sigma(b\bar{b}) = 21.3 * 877.7 * \sigma(t\bar{t})$$

We try to cover a more extended energy range with respect to LHC......

however the ratio between the heavy-quark cross-sections above is expected to decrease relatively slowly.... (in absence of new physics):

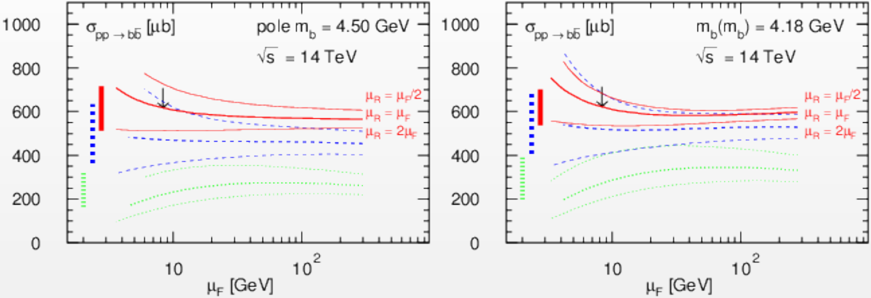
$$\sigma(pp \to t\bar{t}, m_t^{pole} = 172.5 \text{ GeV}) \sim 33624.6 \text{ pb} \quad \text{at} \quad E_{CM} = 100 \text{ TeV}$$

$$\sigma(pp \to b\bar{b}, m_b^{\bar{M}\bar{S}}(m_b) = 4.2 \text{ GeV}) \sim 3374.5\ \mu\text{b} \quad \text{at} \quad E_{CM} = 100 \text{ TeV}$$

$$\sigma(pp \to c\bar{c}, m_c^{\bar{M}\bar{S}}(m_c) = 1.27 \text{ GeV}) \sim 38.2 \text{ mb} \quad \text{at} \quad E_{CM} = 100 \text{ TeV}$$

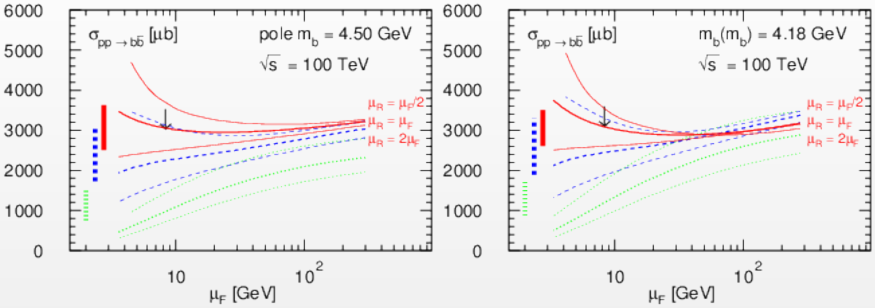
$$\sigma(c\bar{c}) = 11.3 * \sigma(b\bar{b}) = 11.3 * 100.3 * \sigma(t\bar{t})$$

$\sigma(pp \to b\bar{b})$: scale dependence at 14 TeV



* Perturbative convergence in running mass scheme is reached slightly faster than in pole mass scheme.
* Minimal sensitivity to radiative corrections is reached at a scale $\mu_R \sim \mu_F \sim 2m_{bottom}$.
* This translates into a dynamical scale $\sqrt{p^2_{T,charm} + 4m^2_{bottom}}$ to better catch dynamics in differential distributions.

$\sigma(pp \to b\bar{b})$: scale dependence at 100 TeV



∗ Perturbative convergence slightly worse than in the case of 14 TeV.

∗ Minimal sensitivity to radiative corrections is reached at the same scale as before $\mu_R \sim \mu_F \sim 2m_{bottom}$.

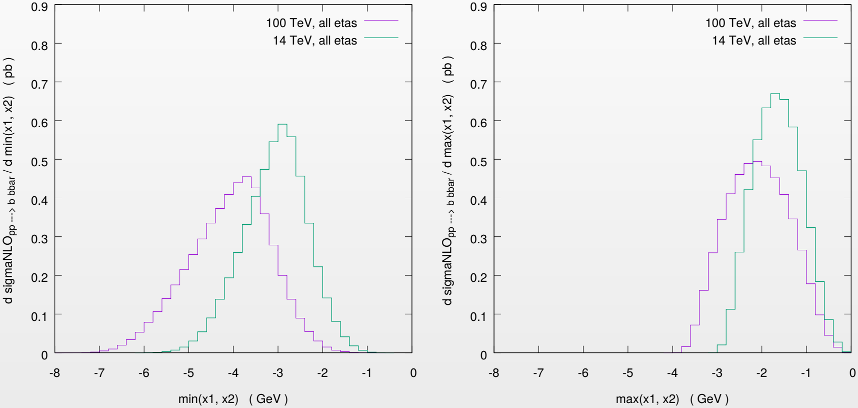
Some fundamental questions

$*$ Are collinear factorization and collinear PDFs still perfectly applicable at 100 TeV ?

$*$ At which energies/kinematical regimes high-energy factorization and transverse momentum dependent PDFs start to play a role ?

$*$ Will the FCC-hh be able to say anything on that ?

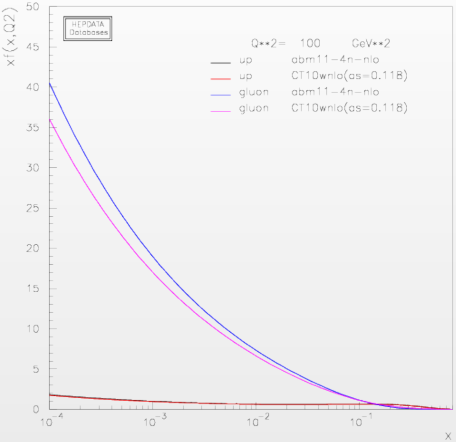
$\sigma(pp \to b\bar{b})$: contributions from initial state partons with different Bjorken-x



$\ast$ At 100 TeV, $\min(x_1, x_2)$ and $\max(x_1, x_2)$ span a wider range than at 14 TeV.

$\ast$ At 100 TeV, $\min(x_1, x_2)$ is peaked around $\sim 10^{-4}$, whereas $\max(x_1, x_2)$ is peaked around $\sim 10^{-2.5}$

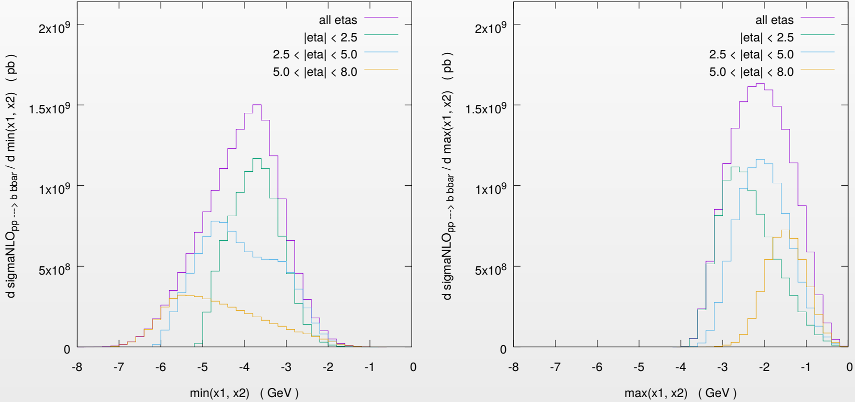
$\sigma(pp \to b\bar{b})$: dependence on gluon PDFs



For $pp \to b\bar{b}$ at 100 TeV, σ_{NLO} (CT10-nlo) $\sim$ 84% σ_{NLO} (ABM11-nlo), but the scale uncertainty is larger.

$\sigma(pp \to b\bar{b})$ in different pseudorapidity ranges:

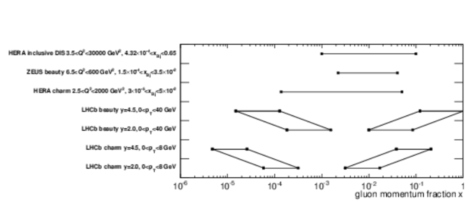
contributions from initial state partons with different Bjorken-x

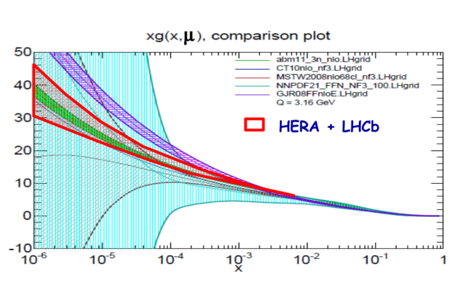


- ∗ We ask for at least 1 b-jet with $|\eta|$ in a fixed interval.
- ∗ At larger $|\eta|$, $\min(x_1, x_2)$ and $\max(x_1, x_2)$ span a wider range than at smaller $|\eta|$.
- ∗ What about PDFs at $x \sim 10^{-6}$?

Towards PDFs at small x

∗ PROSA collaboration paper [arXiv:1503.04581] pointed out the importance of using data collected at LHCb as a complementary tool with respect to those at HERA, to constrain PDFs in (x, Q^2) region unprecedently covered by HERA.

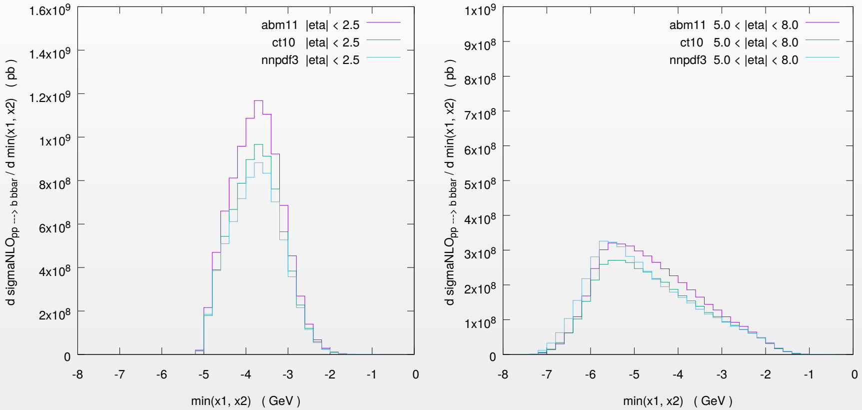




∗ PROSA fit: first fit including some LHCb data (charm and bottom) appeared in arXiv.

∗ NNPDF fit: recent attempt to follow a similar idea (Gauld et al. [arXiv:1506.08025]).

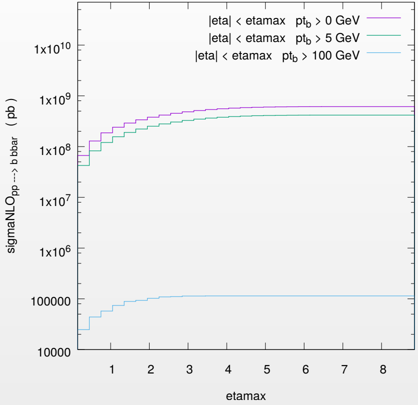
$\sigma(pp \to b\bar{b})$: minimum Bjorken-x and PDFs



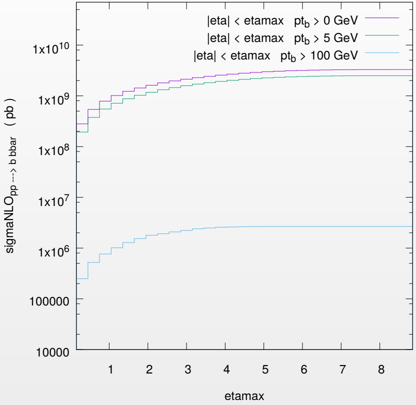
$|\eta| < 2.5$ $\quad\quad$ $5.0 < |\eta| < 8.0$

$*$ At larger pseudorapidities the shapes of $\min(x_1, x_2)$ is particularly sensitive to the PDF choice.

$\sigma(pp \to b\bar{b}, |\eta| < |\eta_{max}|)$ vs $|\eta_{max}|$



$\sqrt{s} = 14$ TeV

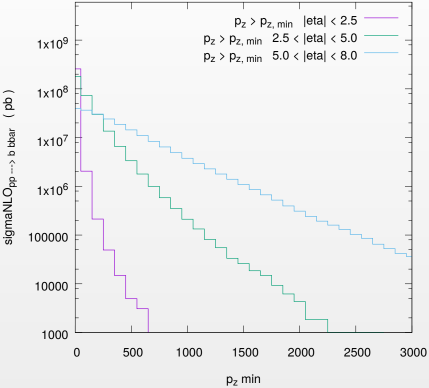


$\sqrt{s} = 100$ TeV

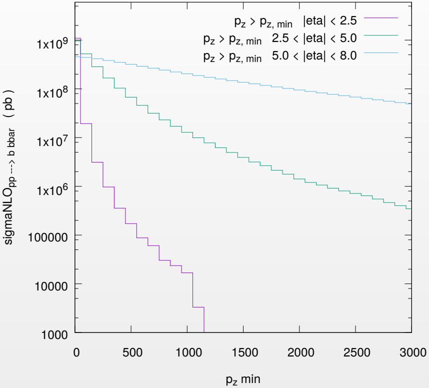
∗ saturation at larger $|\eta_{max}|$ for larger energy.

∗ Important enhancement of the cross-section ($p_T > 100$ GeV) at 100 TeV with respect to the 14 TeV scale ⇒ access to the boosted regime.

$\sigma(pp \to b\bar{b}, p_z > p_{z,min})$ vs $p_{z,min}$



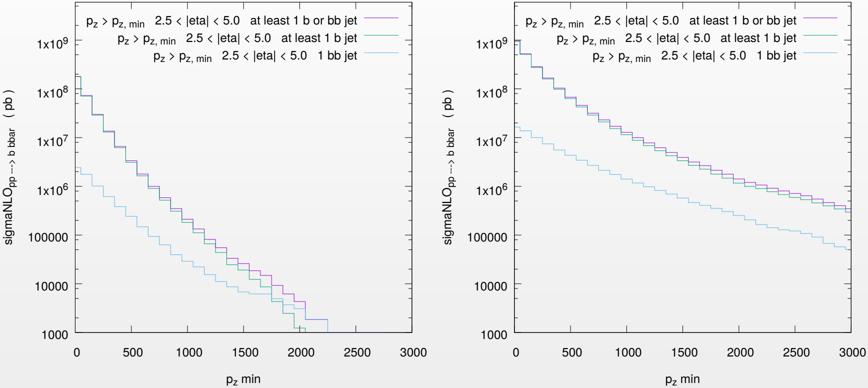
$\sqrt{s} = 14$ TeV



$\sqrt{s} = 100$ TeV

$*$ At larger energy/rapidity larger contribution from forward events.

$\sigma(pp \to b\bar{b}, p_z > p_{z,min})$ vs $p_{z,min}$

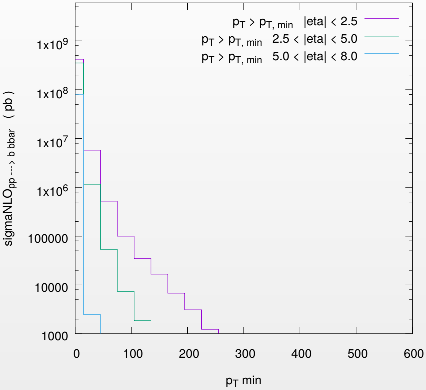


$\sqrt{s} = 14$ TeV

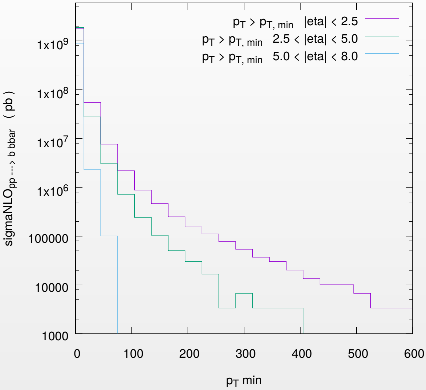
$\sqrt{s} = 100$ TeV

* At larger energy/rapidity larger contribution from events with an highly collimated $b\bar{b}$ jet ($\Delta R_{b\bar{b}} < 0.4$).

$\sigma(pp \to b\bar{b}, p_T > p_{T,min})$ vs $p_{T,min}$



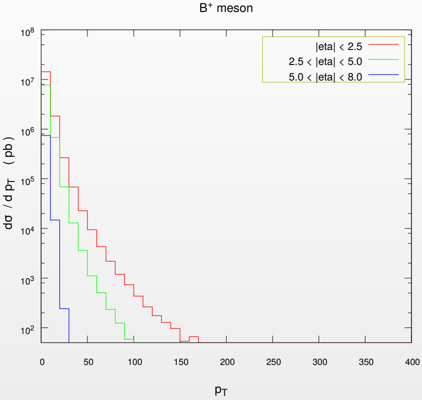
$\sqrt{s} = 14$ TeV



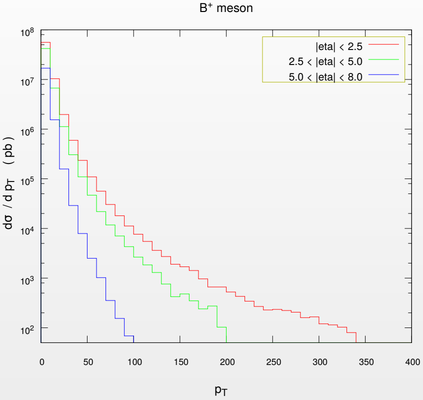
$\sqrt{s} = 100$ TeV

∗ At larger energy/smaller rapidity larger contribution from large p_T events.

p_T distributions of B^+ mesons



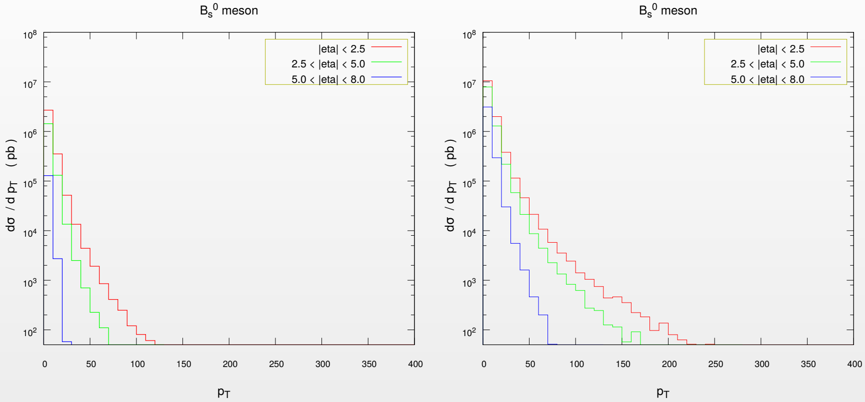
$\sqrt{s} = 14$ TeV



$\sqrt{s} = 100$ TeV

* At larger energy/smaller rapidity, larger contribution from large p_T events.

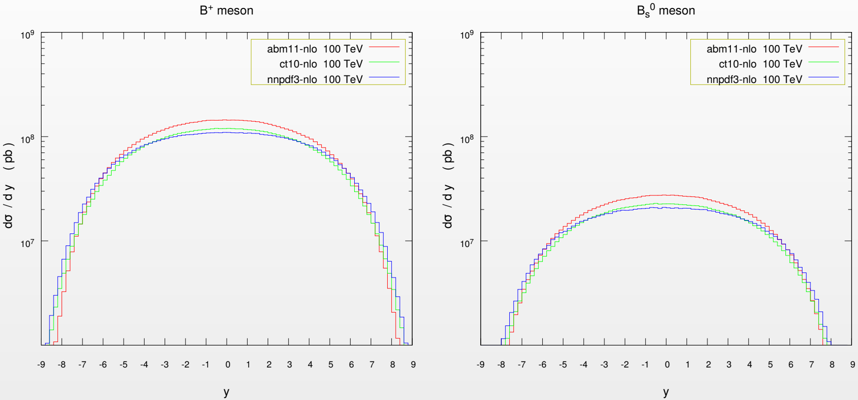
p_T distributions of B_s^0-meson



$\sqrt{s} = 14$ TeV $\qquad\qquad$ $\sqrt{s} = 100$ TeV

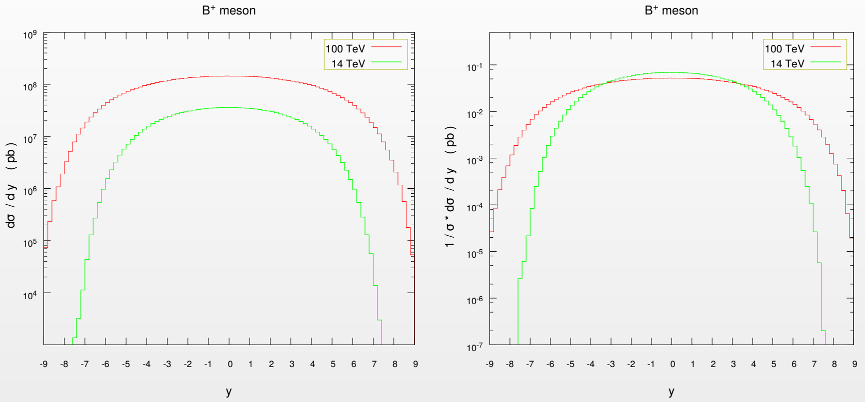
$*$ similar behaviour as for B^+, but with smaller cross-section

y distributions of B mesons: PDF dependence



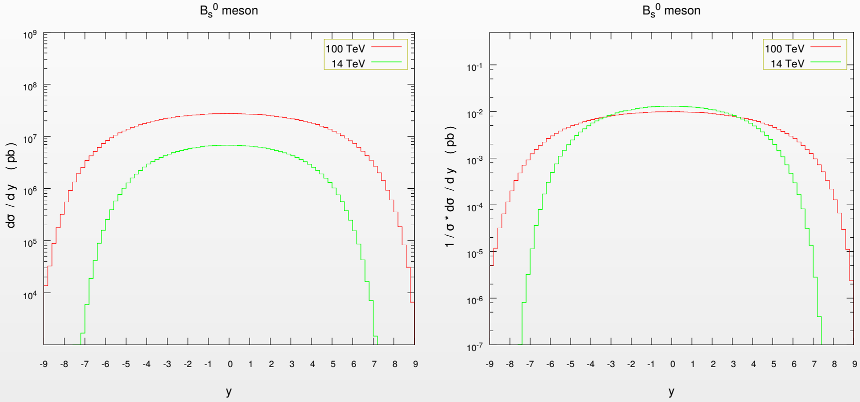
∗ The whole shape of distribution depends on PDF choice.

y distributions of B^+-mesons: energy dependence



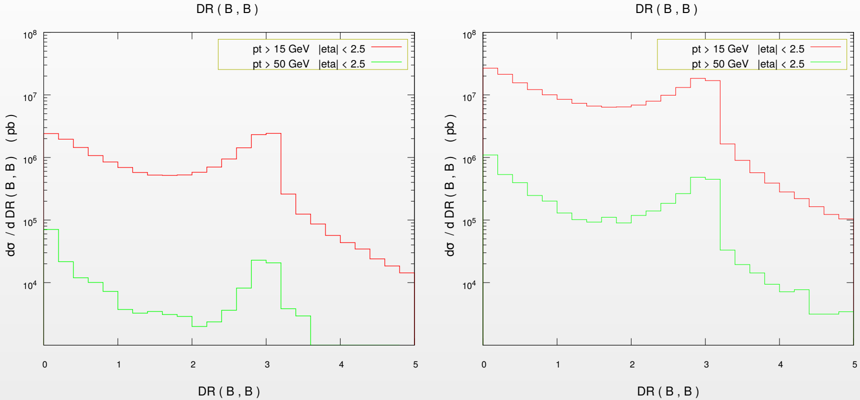
* Different shape of rapidity distributions at 14 TeV and 100 TeV
  $\Rightarrow$ use the ratio (less prone to theoretical errors) to infer PDF behaviour

y distributions of B_s^0-mesons: energy dependence



* similar behaviour as for B^+, but with smaller cross-section

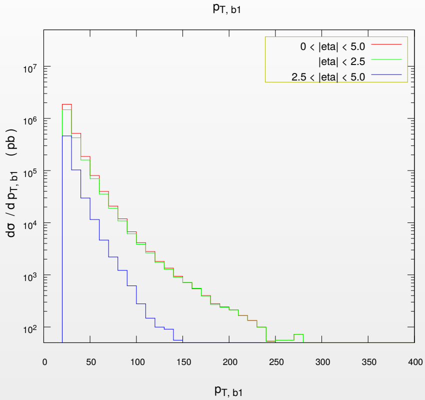
DR correlations between B and $\bar{B}$ hadrons



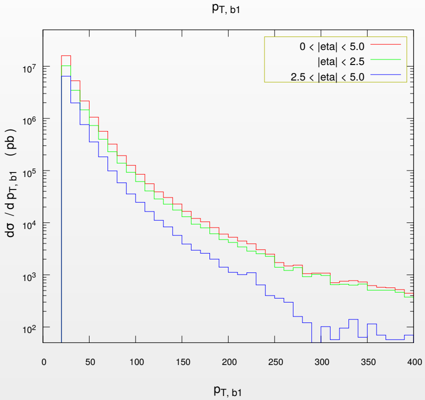
$\sqrt{s} = 14$ TeV $\sqrt{s} = 100$ TeV

* The contribution to the cross-section from (B, $\bar{B}$) pairs emitted in a collimated way increases at larger p_T.

p_T distribution of hardest b-jet



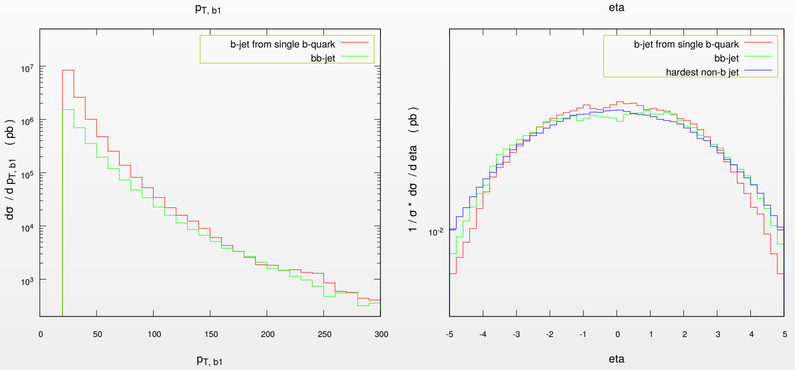
$\sqrt{s} = 14$ TeV



$\sqrt{s} = 100$ TeV

* harder tails at 100 TeV
* jets with large rapidity contribute to the low p_T part of distributions.

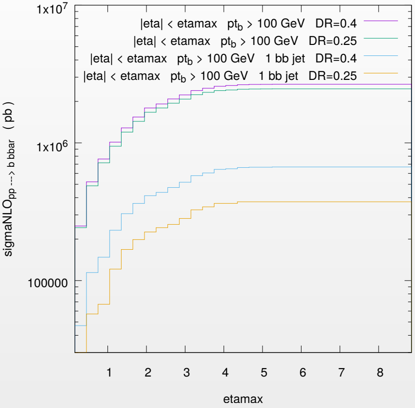
p_T and η distribution of bb jets



$\sqrt{s} = 14$ TeV $\qquad\qquad$ $\sqrt{s} = 100$ TeV

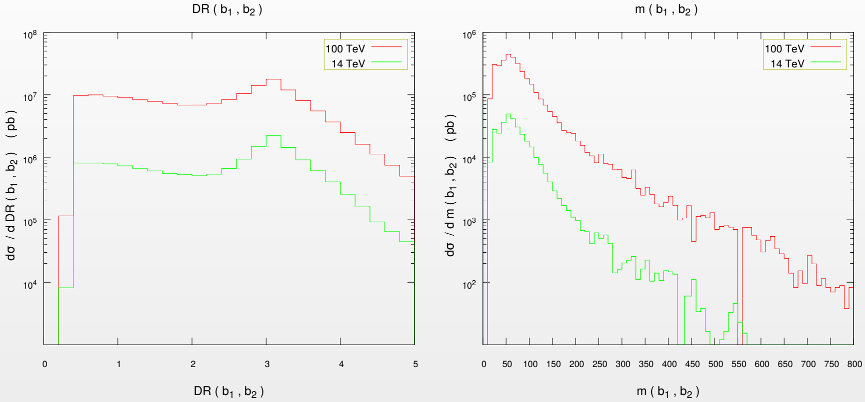
* bb jets are defined by the presence of an highly collimated pair of B hadrons in the same jet ($DR < 0.4$).
* their p_T distribution is harder than that of standard b-jet (i.e. b-jet coming from a single b-quark).
* their rapidity distribution is wider.

Influence of jet-algorithm parameter R



* R choice may affect the value of the cross-section, depending on the cuts.
* In case of high p_T cuts, value of R has to be fixed in order to ensure the best separation between signal and background.

DR and invariant mass distributions of (b, b) jet pair



$\sqrt{s} = 14$ TeV $\qquad\qquad$ $\sqrt{s} = 100$ TeV

* The b-jets here considered track back to the original b-quarks.
* The shape of these distributions is not so affected by the change of $\sqrt{s}$.

Conclusions

$*$ Up to the construction of the FCC collider hopefully a lot of progresses will be done in the developement of the best theoretical frameworks to better address the study of b-jets.

$*$ In this presentation we include some very preliminary distributions for $pp \to b\bar{b}$ at 100 TeV at NLO QCD and NLO QCD + PS accuracy.

$*$ At this accuracy, huge uncertainties come from scale variation, meaning that higher orders are really needed to achieve a better accuracy in the description of this process.

$*$ We did not discuss a lot of other important issues: e.g. b-jet production in association with heavy particles (however treated in following talks), b-jets from the decay of heavy objects, further discussion on jet algorithms for boosted studies, b-tagging at 100 TeV, b-JES............

$*$ For the report: investigate further distributions, possibly peculiar of the 100 TeV regime, separation S/B, alternative use of different tools/theory, estimate of the theoretical uncertainties.....