Roma 1 node

Marco Bonvini + Barbara Mele

INFN, Rome 1 unit

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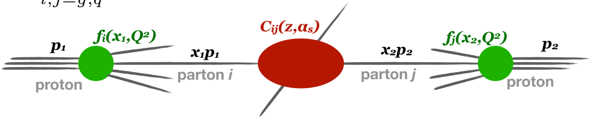
Istituto Nazionale di Fisica Nucleare
Sezione di ROMA

Perturbative QCD

QCD collinear factorization:

$$y = Y - \frac{1}{2}\log\frac{x_1}{x_2}$$

$$\frac{d\sigma}{dQ^2 dY dp_t \ldots} = \sum_{i,j=g,q} \int_\tau^1 dx_1 \int_\tau^1 dx_2\, f_i(x_1,Q^2)\, f_j(x_2,Q^2)\, C_{ij}\left(\frac{\tau}{x_1 x_2}, y, p_t, \ldots, \alpha_s\right)$$



- coefficient functions $C_{ij}(x, y, p_t, \ldots, \alpha_s)$ (observable-dependent, perturbative)
- parton distribution functions (PDFs) $f_i(x, Q^2)$ (universal, non-perturbative)

Altarelli-Parisi (DGLAP) evolution:

$$Q^2 \frac{d}{dQ^2} f_i(x, Q^2) = \sum_{j=g,q} \int_x^1 \frac{dz}{z} P_{ij}(z, \alpha_s(Q^2))\, f_j\left(\frac{x}{z}, Q^2\right)$$

- splitting functions $P_{ij}(x, \alpha_s)$ (universal, perturbative)

PDFs at a given scale Q_0 + DGLAP evolution $\to$ PDFs at any scale Q
Strategy: fit $f_i(x, Q_0^2)$ by comparing theory predictions to many data

All-order resummation of enhanced logarithms

In general, perturbative coefficients contain logarithms of dimensionless ratios

$$L = \left\{ \log(1-x), \quad \log\frac{1}{x}, \quad \log\frac{p_t^2}{Q^2}, \quad \log(\text{something else}), \quad \ldots \right\}$$

Sometimes, they are logarithmically enhanced:

$$\begin{aligned} P_{ij}(x,\alpha_s) \text{ or } C_{ij}(x,y,p_t,\ldots,\alpha_s) = \quad & a_0 \\ & + \alpha_s \left[a_1 L + b_1\right] \\ & + \alpha_s^2 \left[a_2 L^2 + b_2 L + c_2\right] \\ & + \alpha_s^3 \left[a_3 L^3 + b_3 L^2 + c_3 L + d_3\right] \\ & + \alpha_s^4 \left[a_4 L^4 + b_4 L^3 + c_4 L^2 + d_4 L + e_4\right] \\ & + \ldots \end{aligned}$$

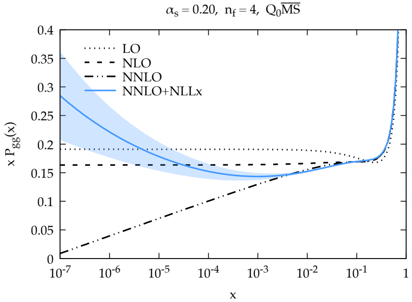
If/when $\alpha_s L \sim 1$ the fixed-order expansion is no longer predictive!

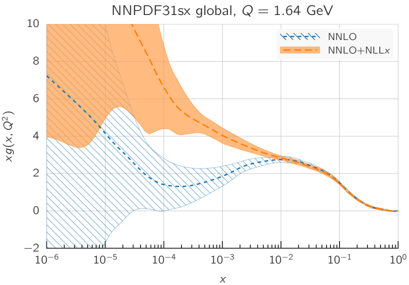
Resum the logs, and convert to a "logarithmic-order" expansion:

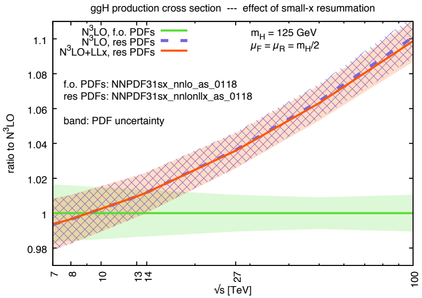
$$g_{\rm LL}(\alpha_s L) + \alpha_s\, g_{\rm NLL}(\alpha_s L) + \alpha_s^2\, g_{\rm NNLL}(\alpha_s L) + \alpha_s^3\, g_{\rm N^3LL}(\alpha_s L) + \ldots$$

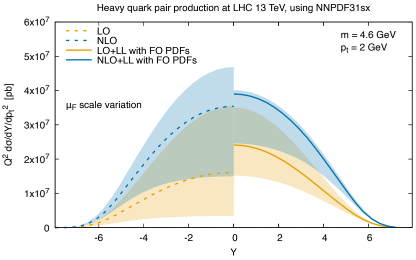
Leading log (LL), next-to-leading log (NLL), next-to-next-to-leading log (NNLL)...

Small-x resummation









Future plans for resummation

- Phenomenology of small-x resummation
- Extension of small-x resummation to NLL (currently available at LL only)
- Combination of small-x resummation and threshold (large-x) resummation (relevant for high rapidity, e.g. for the Forward Physics Facility at CERN)
- Interplay of threshold resummation and heavy quark production
- ...

Theory uncertainty from missing higher orders

Canonical approach: **Scale variation:** dependence on unphysical scales of a physical observable at N^{n}LO is of higher order

$$\sigma_{\mathrm{N}^n\mathrm{LO}}(\mu) = \sum_{k=0}^{n} c_k(\mu)\alpha_s^k(\mu) \qquad \mu\frac{d}{d\mu}\sigma_{\mathrm{N}^n\mathrm{LO}}(\mu) = \mathcal{O}(\alpha_s^{n+1})$$

Canonical uncertainty: variation by a factor of 2 about a "central" scale μ_0

$$\sigma_{\mathrm{true}} \approx \sigma_{\mathrm{N}^n\mathrm{LO}}(\mu_0) \pm \max_{\mu_0/2\leq\mu\leq 2\mu_0} \left|\sigma_{\mathrm{N}^n\mathrm{LO}}(\mu) - \sigma_{\mathrm{N}^n\mathrm{LO}}(\mu_0)\right|$$

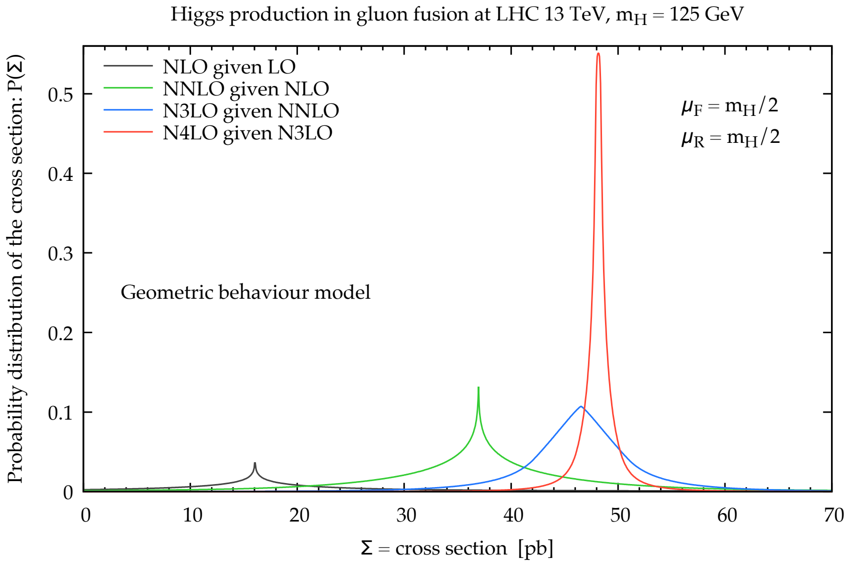
Which central scale μ_0?
How much should I vary the scale?
How do I interpret the uncertainty?

Need for a statistically-sound definition of theoretical uncertainties, which does not depend so much on arbitrary assumptions

Theory uncertainty from missing higher orders should be a **probability distribution**

First pioneering work in this direction: [Cacciari,Houdeau 1105.5152]

Higgs in gluon fusion at LHC: probability distributions



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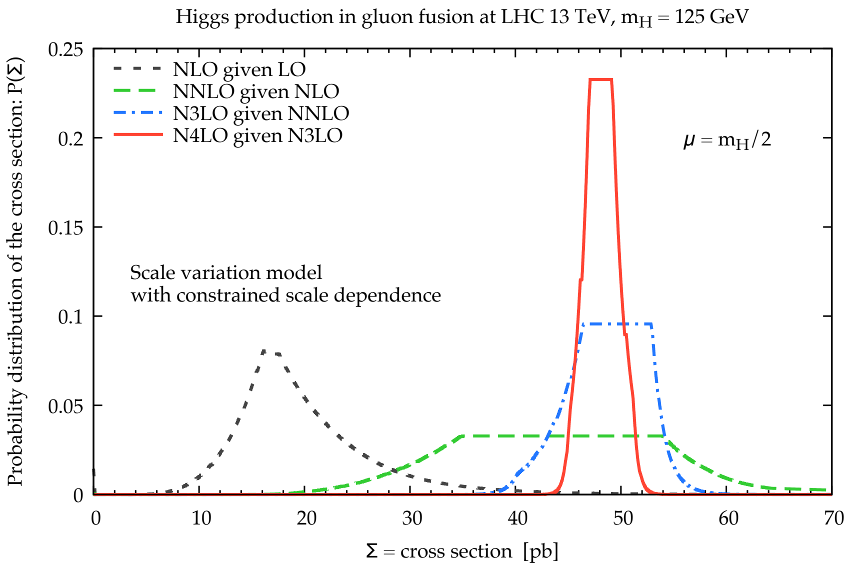
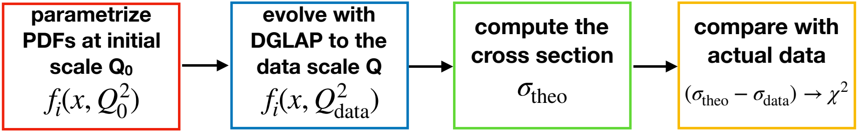


Proton's PDFs are fitted from data



Improve determination of PDFs with improved theoretical description, e.g. with resummation

Studies of PDF parametrizations

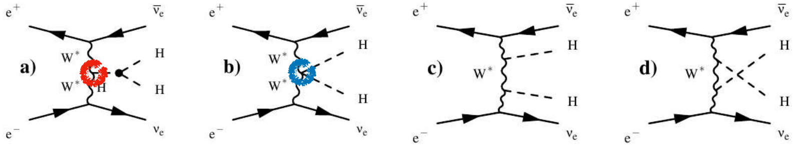
Muon's PDFs can be computed perturbatively!

Essential ingredient for a muon collider.
Ongoing studies on impact of small-x resummation for a ~ 10 TeV collider.

trilinear Higgs coupling at Muon Colliders

$$\mathcal{L} = -\frac{1}{2}m_h^2 h^2 - \lambda_3 \frac{m_h^2}{2v} h^3 - \lambda_4 \frac{m_h^2}{8v^2} h^4$$

✱ 40.000 HH pairs at 14 TeV !



$HH \to 4b$

$p_T(b) > 30$ GeV, $\quad 10^\circ < \theta_b < 170^\circ, \quad \Delta R_{bb} > 0.4. \quad |m_{jj} - m_H| < 15$ GeV

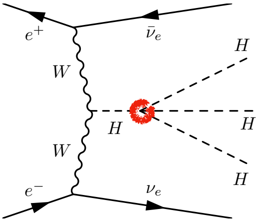
$\sqrt{s}$ (TeV)	3	6	10	14	30	(other projects)
benchmark lumi (ab^{-1})	1	4	10	20	90	
HHWW $(\Delta\kappa_{W_2})_{in}$	5.3%	1.3%	0.62%	0.41%	0.20%	5% CLIC
HHH $(\Delta\kappa_3)_{in}$	25%	10%	5.6%	3.9%	2.0%	5% FCC-hh 68%CL

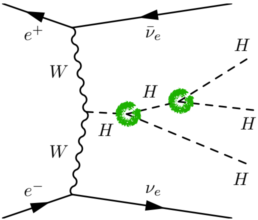
(95% CL, single-parameter fit)

T. Han et al. arXiv:2008.12204

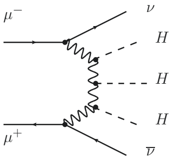
$\mu^+\mu^- \to HHH\nu\bar{\nu},\ (\nu = \nu_e, \nu_\mu, \nu_\tau)$

$$V_\mathrm{h} = \frac{m_h^2}{2}h^2 + (1+\delta_3)\lambda_{hhh}^{\mathrm{SM}} v h^3 + \frac{1}{4}(1+\delta_4)\lambda_{hhhh}^{\mathrm{SM}} h^4$$



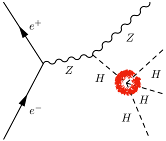


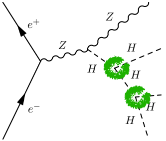
$$\mu^+\mu^- \to W^*W^*\nu_\mu\bar{\nu}_\mu$$
$$\to HHH\nu_\mu\bar{\nu}_\mu$$



+ . . .

$$\sigma = c_1 + c_2\delta_3 + c_3\delta_4 + c_4\delta_3\delta_4 + c_5\delta_3^2 + c_6\delta_4^2 + c_7\delta_3^3 + c_8\delta_3^2\delta_4 + c_9\delta_3^4$$





HHHZ subdominant !

σ_{HHHZ} ~ 1/2 $\sigma_{HHH\nu\nu}$ @ 3TeV

~ 1/50 $\sigma_{HHH\nu\nu}$ @ 30TeV

$(N-N_{SM})/\sqrt{N_{SM}} \sim 1$ vs (δ_3, δ_4)

VBF→HHH

arXiv:2003.13628

$$\lambda_3 = \lambda_{SM}(1+\delta_3)$$

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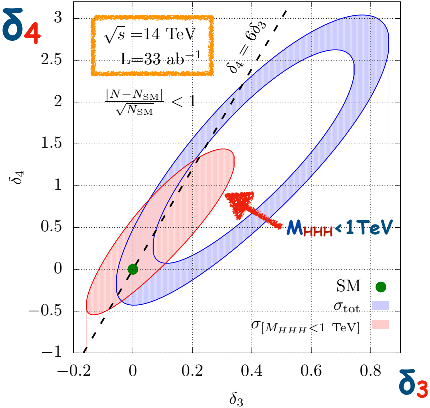
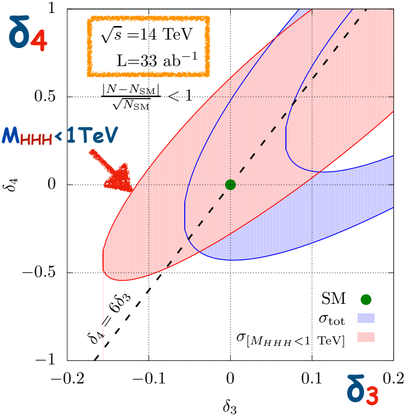
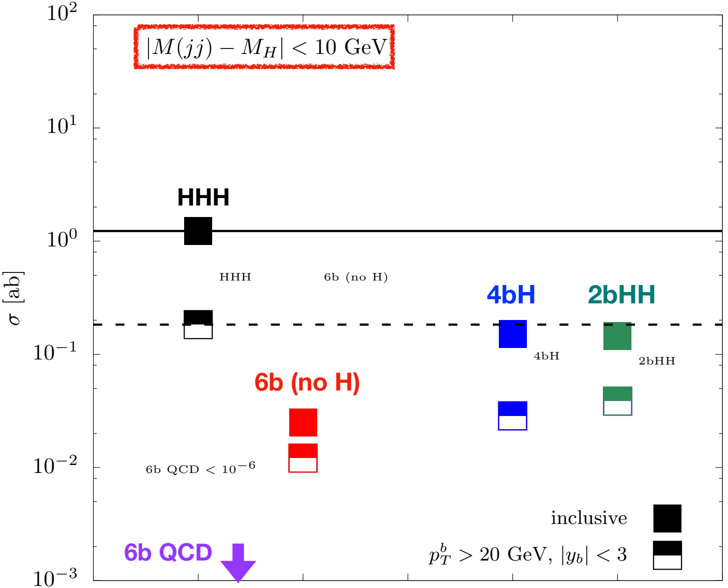
$\sqrt{S_{\mu\mu}}$ = 14 TeV





[δ_3=0] $-0.3 < \delta_4 < 0.5$ (68%CL) !!!

with m_H reconstruction (10GeV)



outlook

- testing Higgs potential via Higgs self-coupling measurement of paramount importance !
- triple Higgs production only direct access to quartic self-coupling
- projections at FCC-hh can give few-% accuracy on λ_3 but only mild bounds on λ_4 ($\delta\lambda_4/\lambda_4 \sim 10$) at present
- first indications that μ colliders @10+TeV with $L \sim 10^{35} cm^{-2} s^{-1}$ might provide a λ_4 determination with few-10% accuracy ($\delta\lambda_4/\lambda_4 \sim 1$)
  → → significantly better that other future projects !
- physics bckgds expected mild (also for hadronic final states) → preliminary detailed simulations confirm !
  optimal bckgd suppression requires good resolution in M(jj) reconstruction !

Outlook

BM, talk at 7th FCC-ee Phys. WS June 2014

- ever since its discovery, the top quark has never been produced and studied in such a clean environment as the one expected in e^+e^- collisions

- e^+e^- collisions will almost allow to trace back top-quark final states on an event-by-event basis

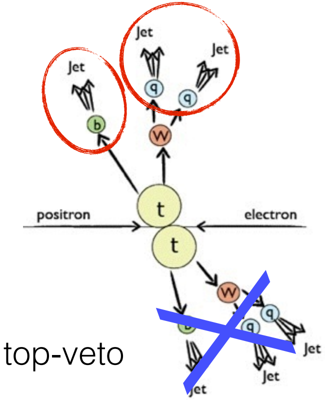
- this will open the opportunity to look at details of top production and kinematics that is unthinkable in hadron collisions (relevant strategies mostly still to be developed …)

- rare top decays is one of the (many) top physics chapters that would widely benefit from such spectacularly clean environment !

example →

inclusive searches for exotic t decays via recoil system

large variety
of exotic final states
(unexpected signatures "hard" at LHC !)
➜ global analysis of a top
recoil system with a top-veto



$E_{cm}(e+e-) \geq 350$ GeV

a) define criteria to tag
a Wb/Wj system
as a (SM) top quark

b) look for events containing
a top-system with
a veto on a 2nd tag
(i.e. recoil system does not pass
the SM top-system criteria)

c) full simulation needed to
assess sensitivity (<% σ ?)

d) get model-independent
bounds on $BR(top)_{exotica}$!