Heavy-quark production and further recent developments in SIBYLL

R. Engel, A. Fedynitch, T.K. Gaisser, Felix Riehn and T. Stanev

HQHP2019 - Mainz

30. September 2019

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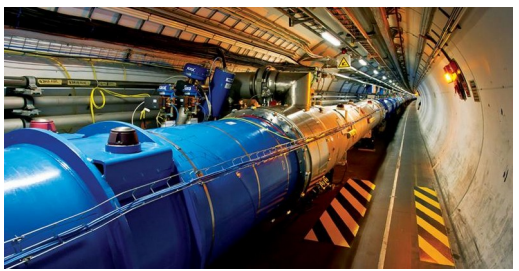
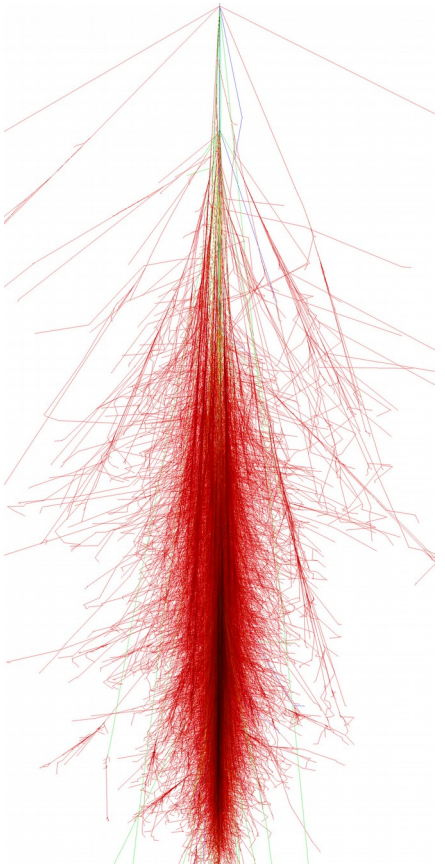
Origin of SIBYLL

First version ~1992

“Slow computers, fast programs”

(IBM)





Minimal requirements:

* QCD (rising cross section, multiplicity etc)
* efficient code
* Projectiles: p, pi, K and nuclei up to Fe
* ultra-high energies, 150 TeV cm
* Forward phase space

One, two, three … hadronic event

One: how many scatterings?

$$a(s,\vec{b}) = \frac{i}{2}(1 - e^{-\chi_{\rm soft}(s,\vec{b}) - \chi_{\rm hard}(s,\vec{b})})$$

Eikonal amplitude (unitarity)

$$\sigma_{QCD}(s, p_T^{min}) = K \int_{p_T^{min}}^{\infty} dp_T \int dx_1 \int dx_2 \sum_{i,j,k,l} f_i(x_1, Q^2) f_j(x_2, Q^2) \frac{d\hat{\sigma}^{i,j\to k,l}}{dp_T}(\hat{s}, \hat{t})$$

LO QCD cross section

$$\sigma_{\rm soft} = \mathcal{A}\left(\frac{s}{s_0}\right)^{-\epsilon} + \mathcal{B}\left(\frac{s}{s_0}\right)^{\Delta}$$

Donnachie-Landsoff

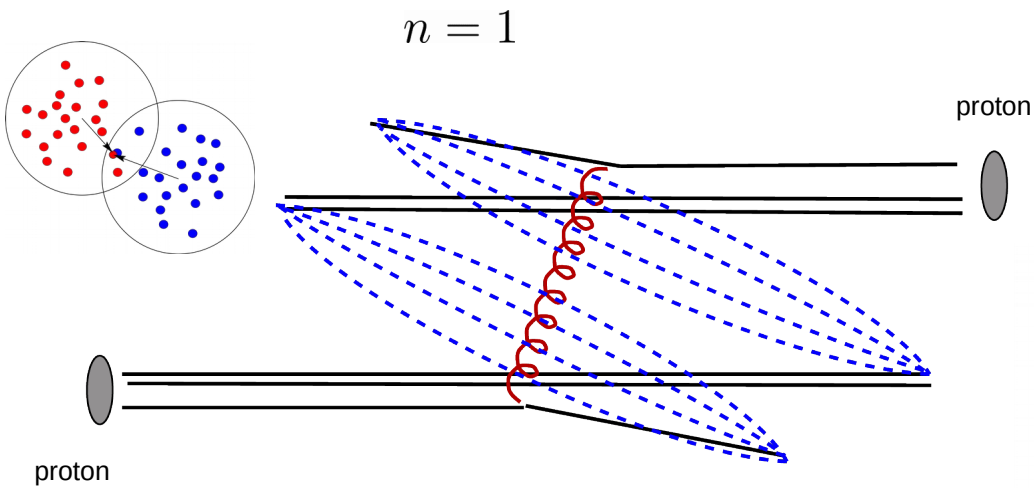
PDF: GRV98
Hadron profiles
PtMin separate hard & soft
Two channel optical model –> diffraction

Optical theorem, AGK rules

$\sigma_{N_{\rm h},\, N_{\rm s}}$

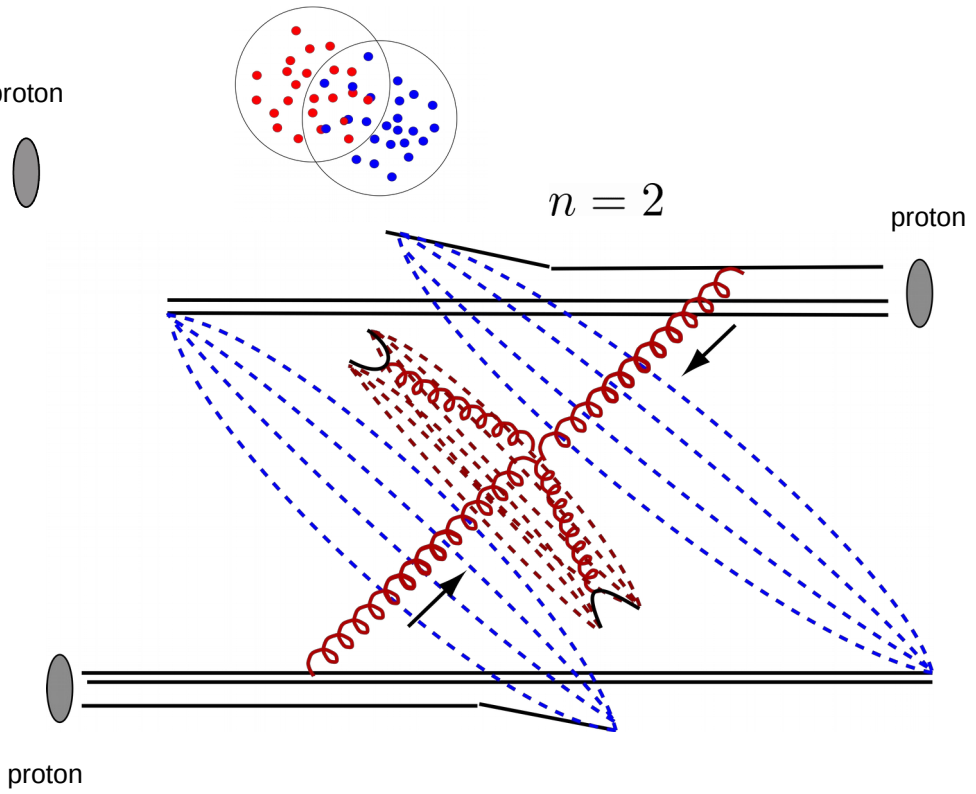
→ Calculated ‘offline’

Two: parton momenta



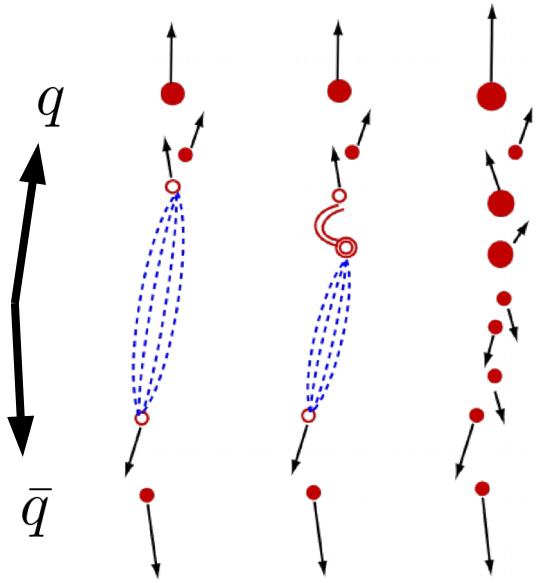
→ combine u:d:s:c:g → partons

$$f(x) = g(x) + \frac{4}{9}[q(x) + \bar{q}(x)]$$



etc.

Three: string fragmentation

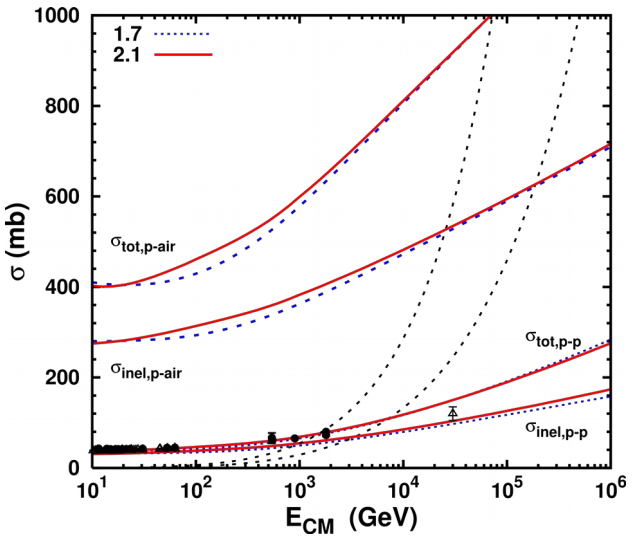


$$f(z) = \frac{(1-z)^{\alpha}}{z} e^{-bm_{\mathrm{T}}/z}$$

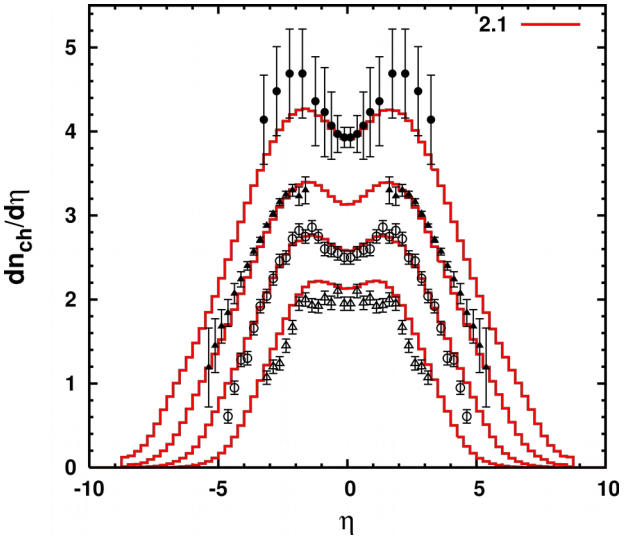
$$f_{\mathrm{lead}}(z) = z^{\beta}$$

Parameters	Value
u,d : s	0.3
qq : q	0.04
Spin0 : spin1	0.3

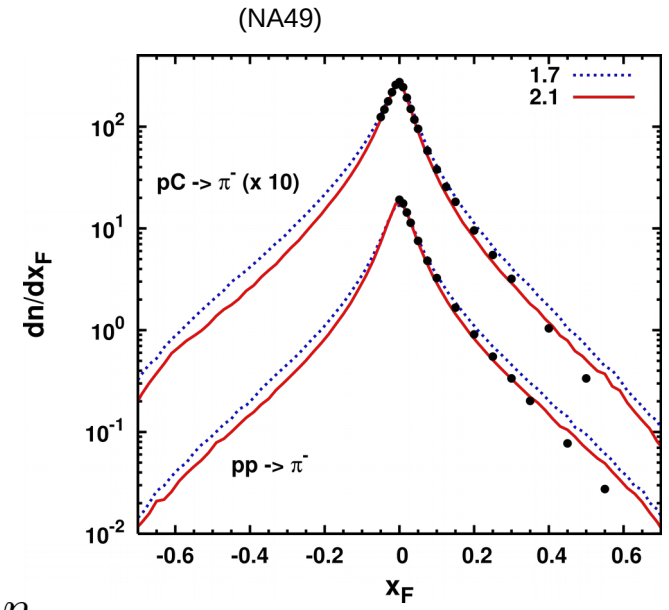
Model performance

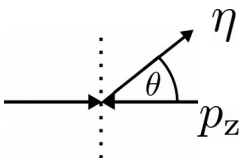


(CDF, UA5, NA22)



(NA49)





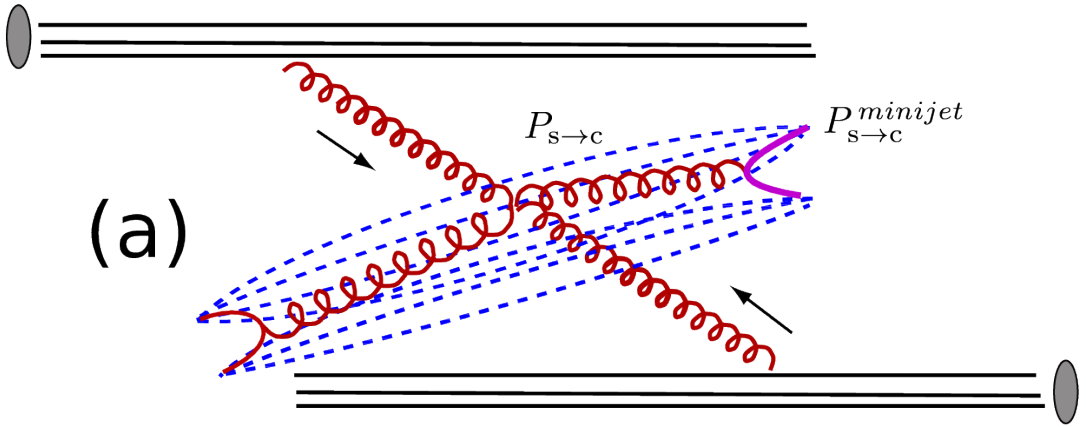
Sibyll 2.1

tuned to TeVatron

Charm production

$$m_{\mathrm{c}} \approx 2\,\mathrm{GeV} \;\rightarrow\; \mathrm{pQCD} \;\rightarrow\; \mathrm{minijets}$$

Charm production in SIBYLL



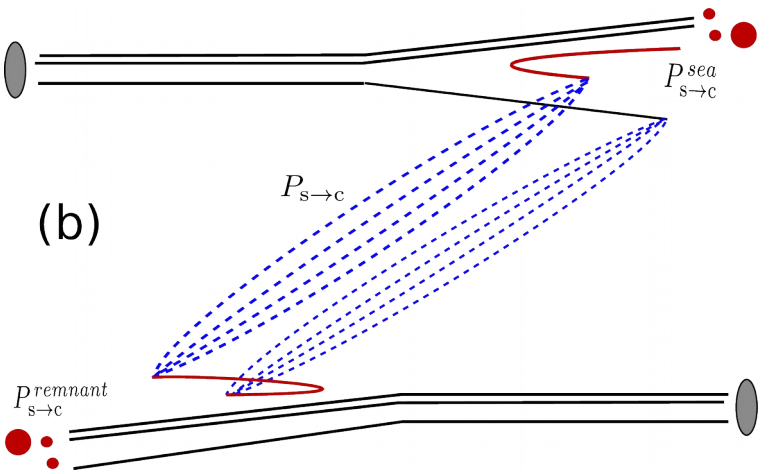
central

Parameter : P_{c}

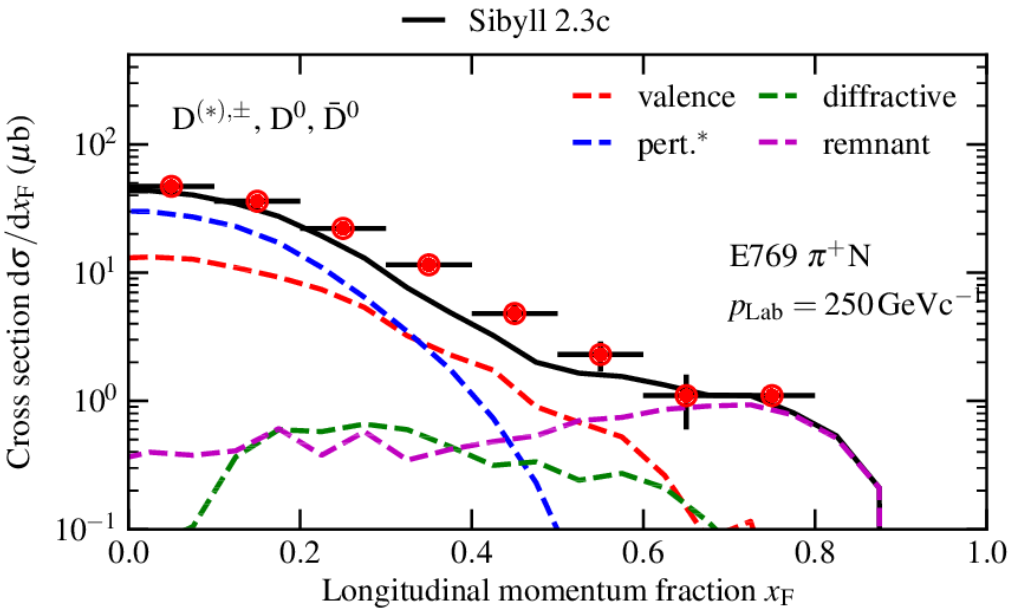
Rate of charm in quark sampling

Evidence for leading, soft charm (SELEX)

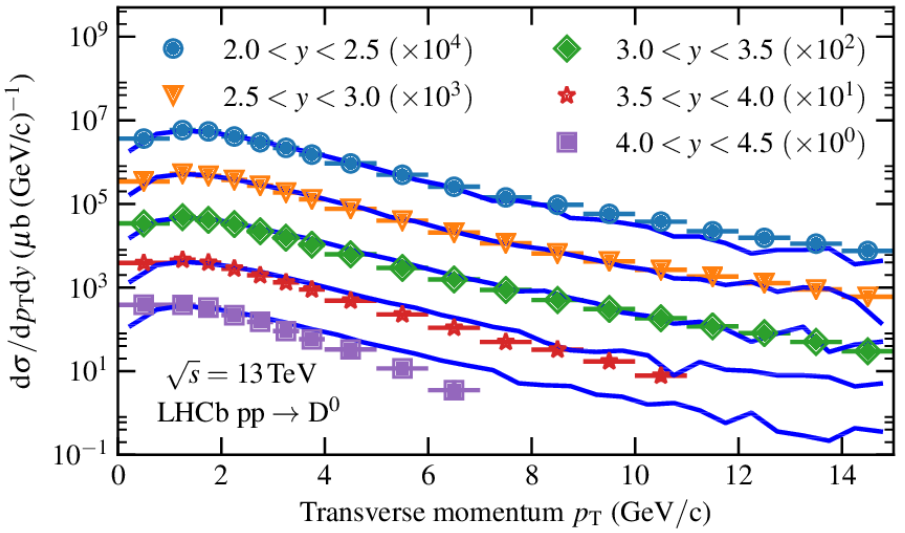
forward



Charm tuning

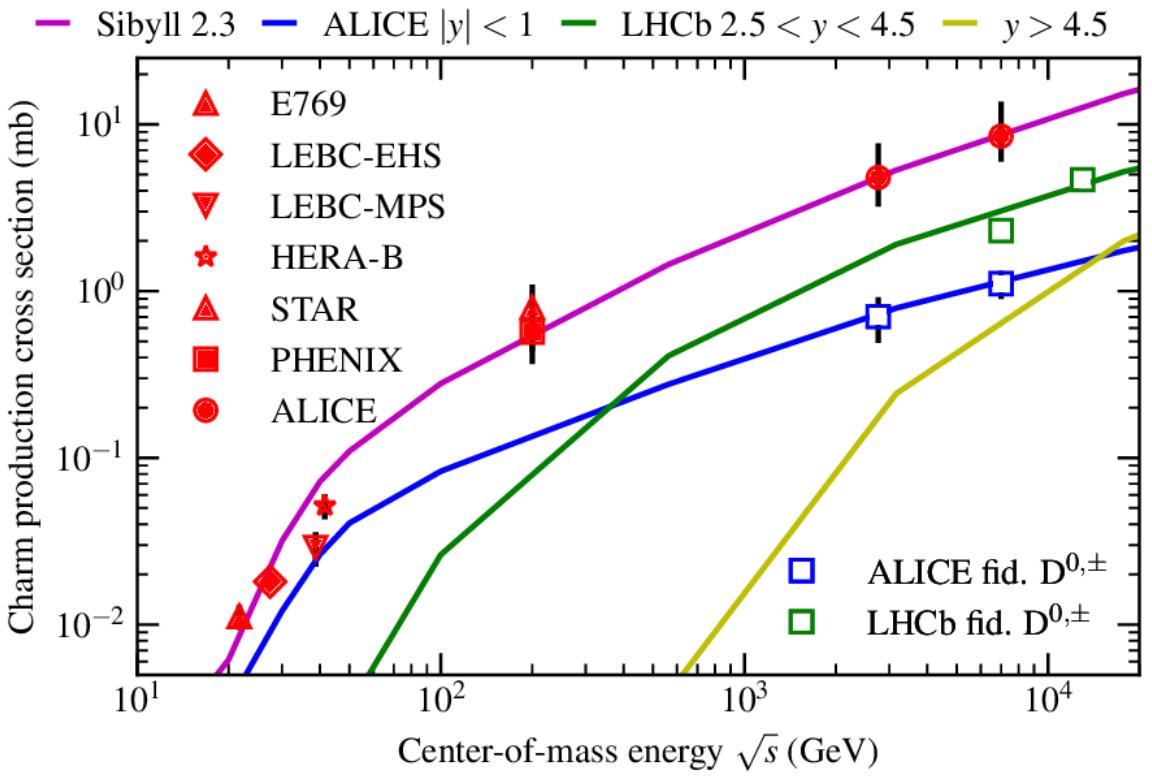


Fixed target
Fix shape!



LHC, fix pert.*

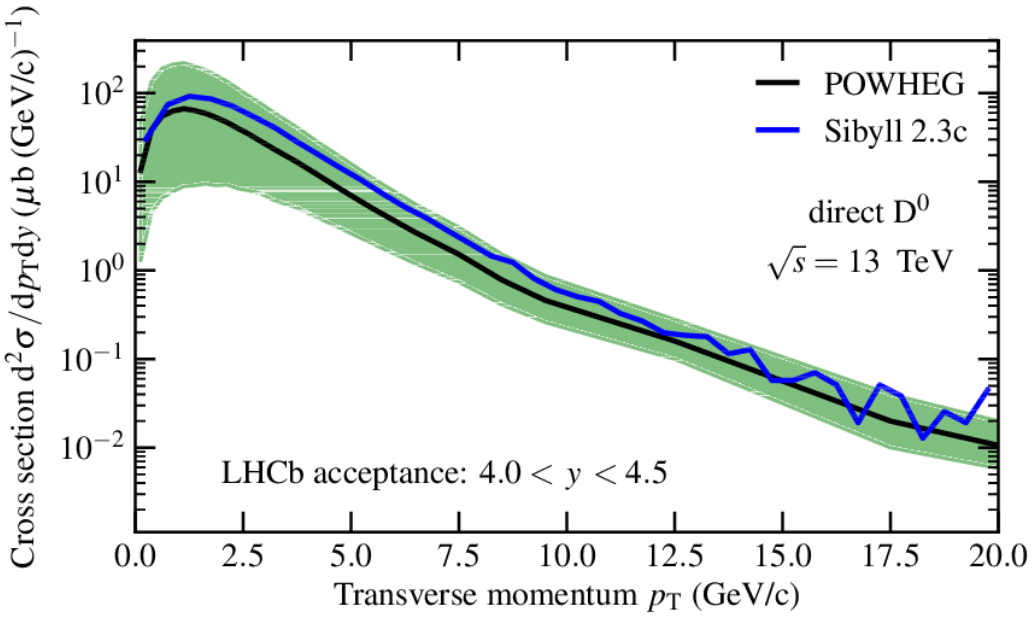
Inclusive charm cross section



parameter	value
perturbative	
$P_{s\to c}^{\text{minijet}}$	0.08
non-perturbative	
$P_{s\to c}^{\text{soft}}$	0.004
$P_{s\to c}^{\text{sea}}$	0.002
$P_{s\to c}^{\text{remnant}}$	0.0
$P_{s\to c}^{\text{string}}$	0.004

Sibyll vs. NLO

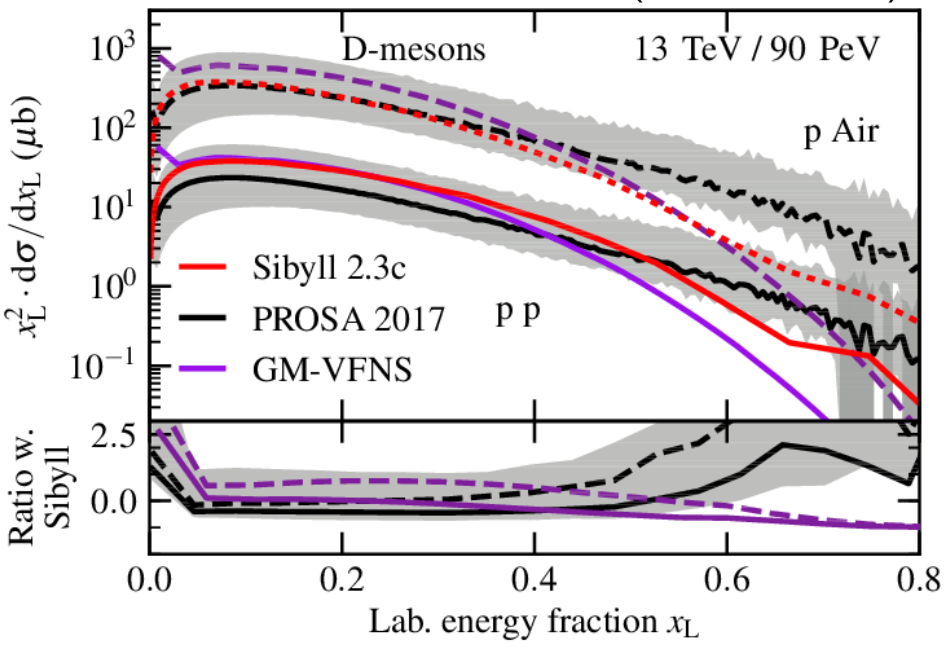
central



Good agreement

Full long. phasespace

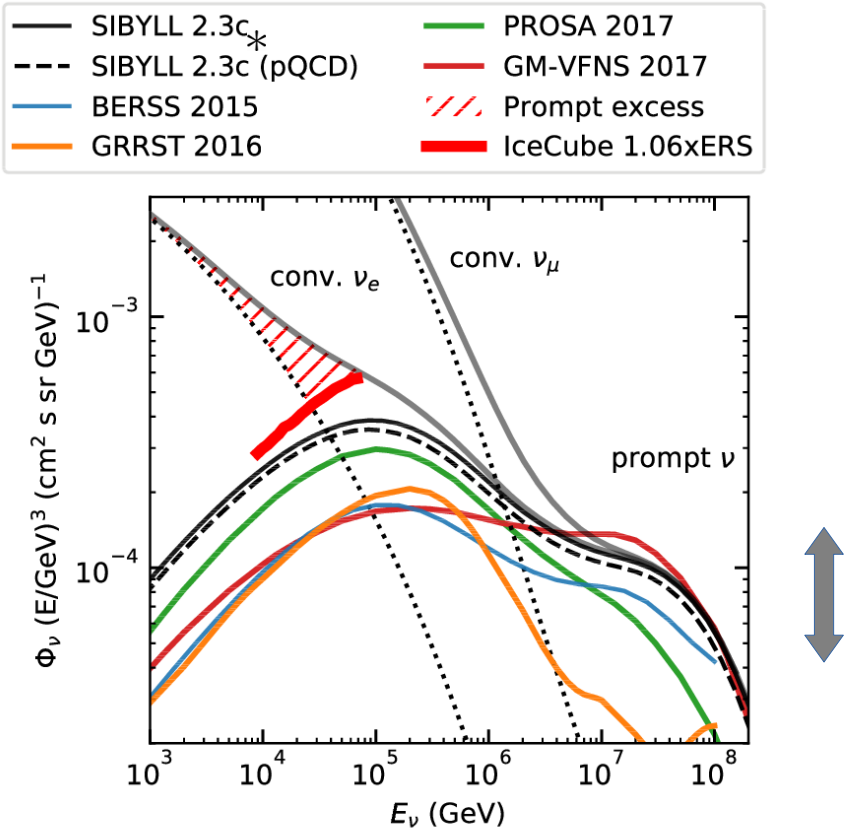
(with M.V. Garzelli)



Not so much

Flux predictions

Atmospheric flux



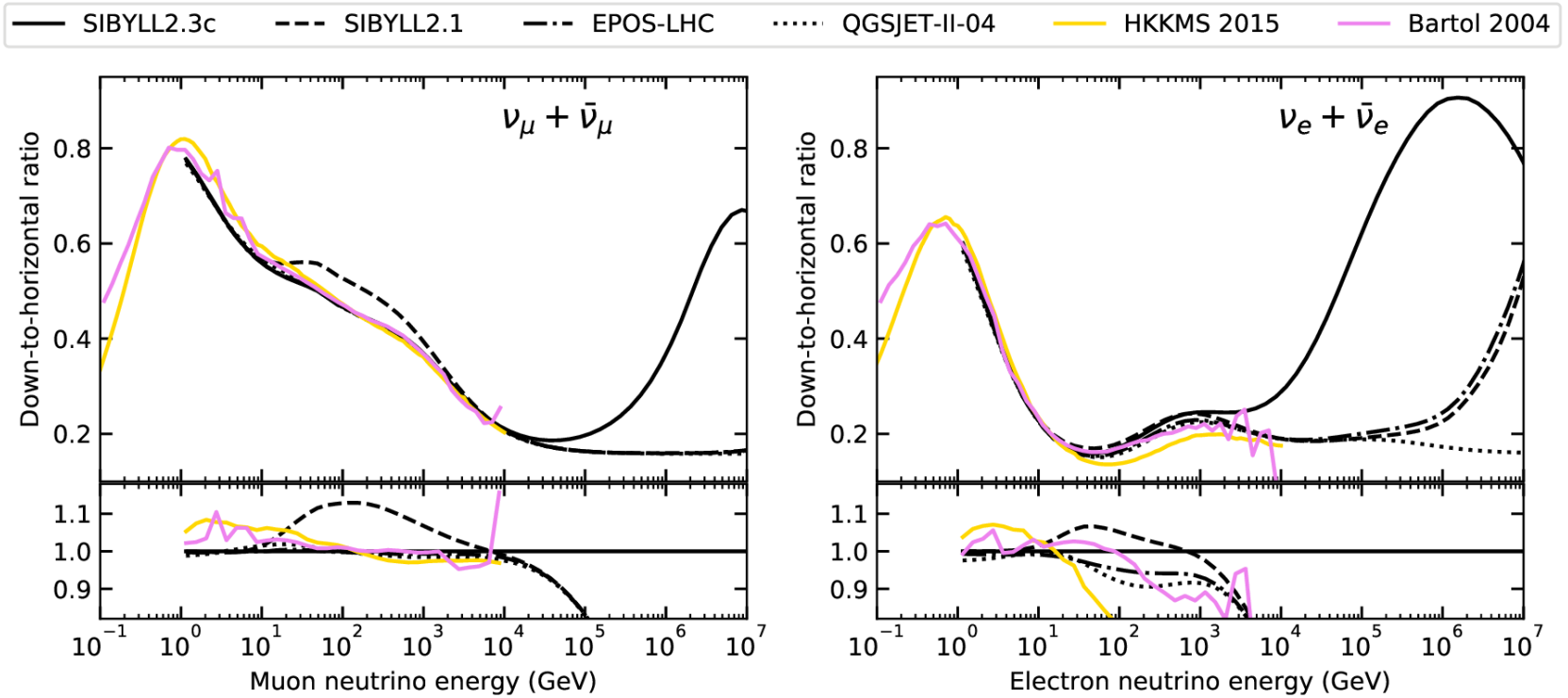
Range of predictions ??

what happened with pQCD works ?

→ additional modeling:

* nuclear interaction
* phasespace extrapolation

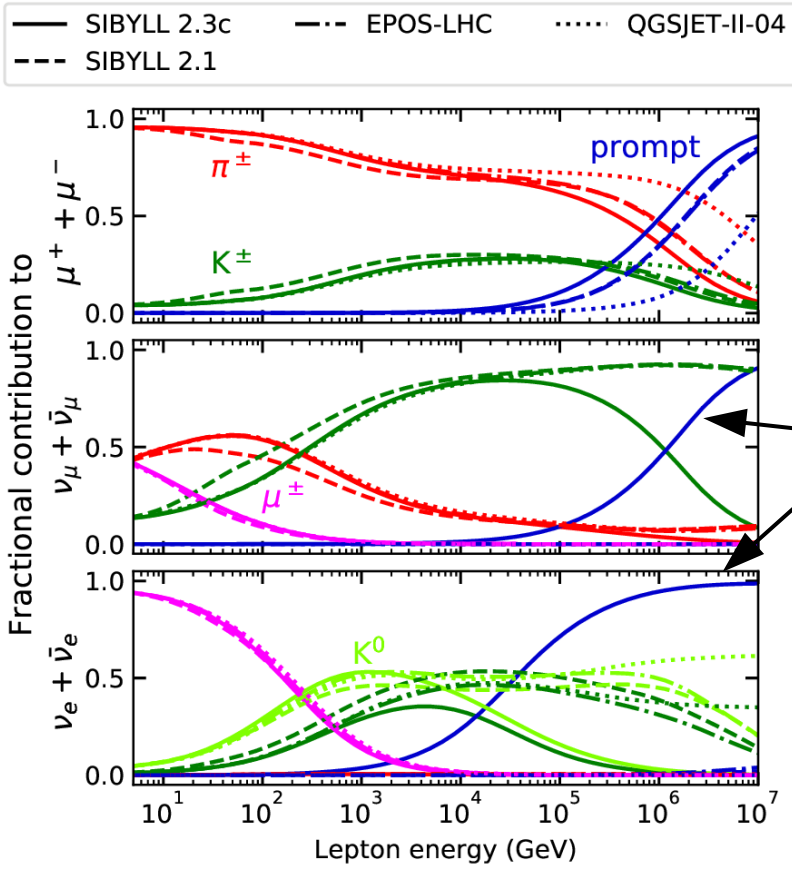
Down-to-horizontal ratio



Measures prompt vs. Non-prompt

Or First vs. Secondary interactions

Flux decomposed

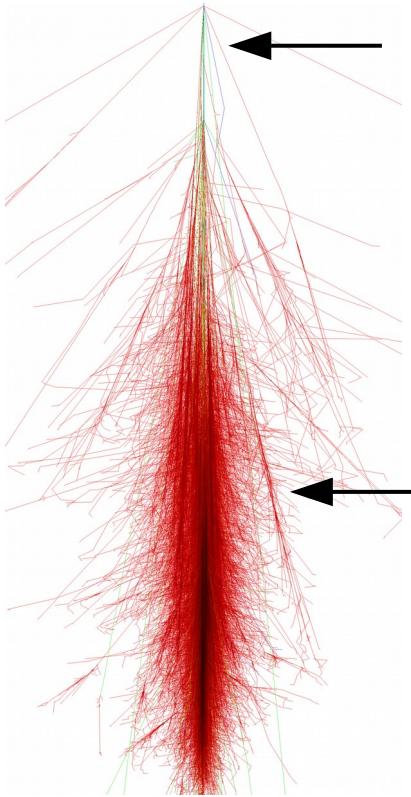


Prompt muons also from ‘unflavored’ mesons $\eta\ \omega\ \rho^0\ \ldots$

Prompt neutrinos only for Sibyll → charm!

How reliable are these predictions ?

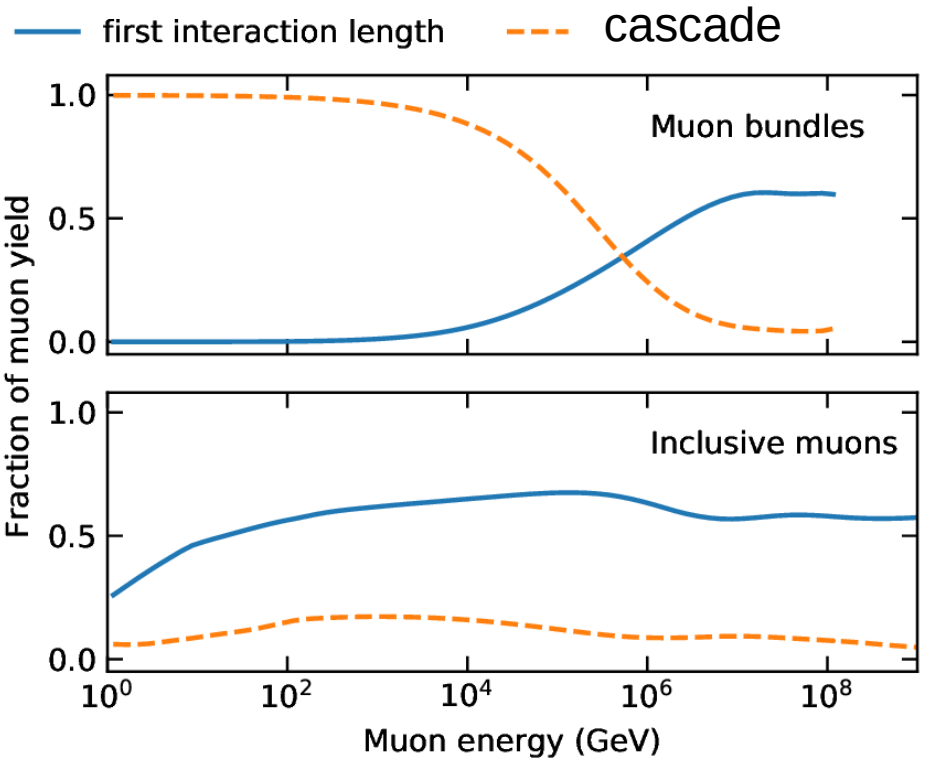
Where in the air shower?



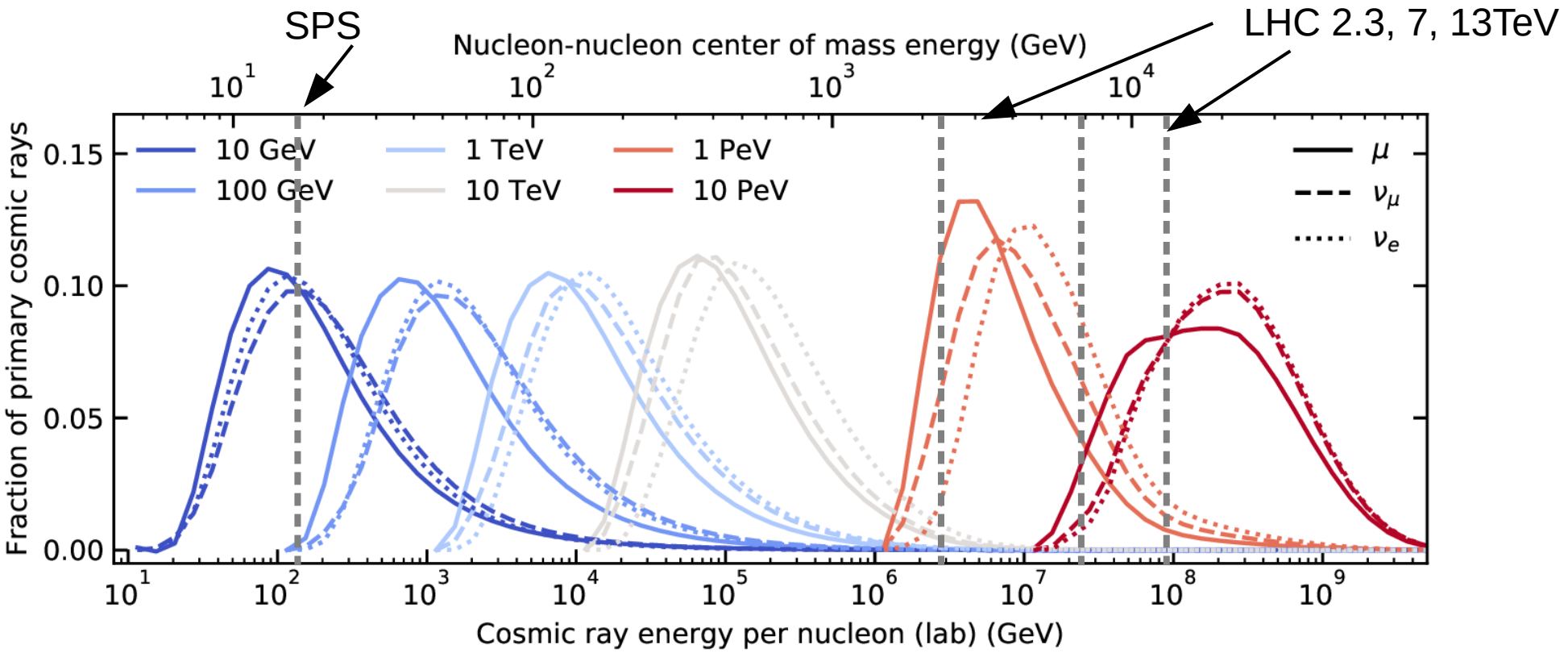
First interaction

(including decay of products)

cascade



Primary energy



LHC: our tool!

Phasespace

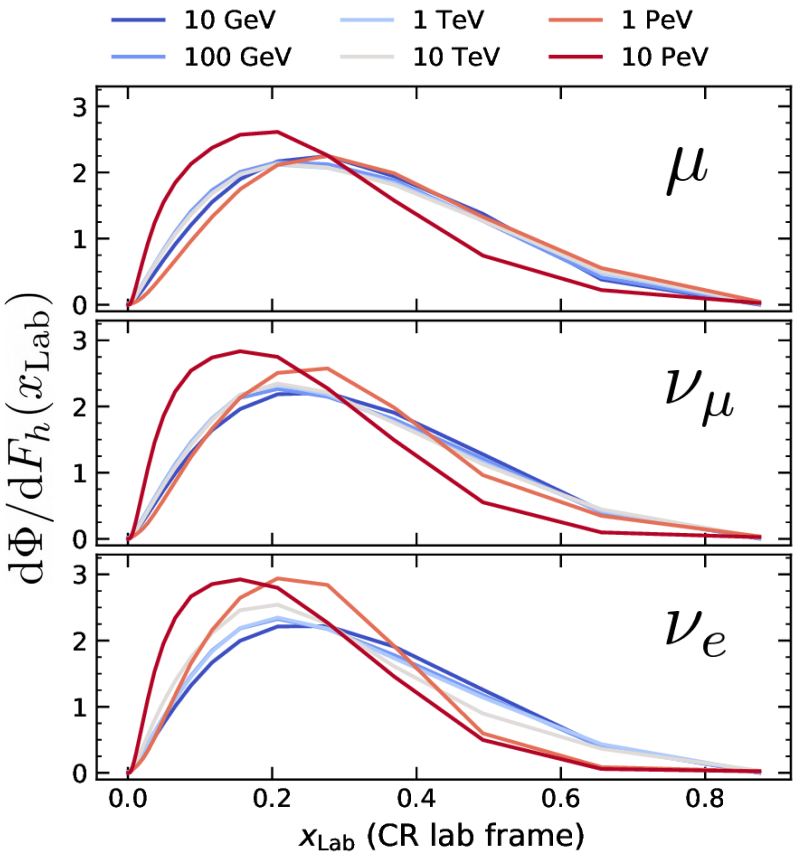
The coupled cascade equations

$$\frac{\mathrm{d}\Phi_h(E,X)}{\mathrm{d}X} = -\frac{\Phi_h(E,X)}{\lambda_{\mathrm{int},h}(E)} - \frac{\Phi_h(E,X)}{\lambda_{\mathrm{dec},h}(E,X)} - \frac{\partial}{\partial E}(\mu(E)\Phi_h(E,X)) + \sum_\ell \int_E^\infty \mathrm{d}E_\ell \frac{\mathrm{d}N_{\ell(E_\ell)\to h(E)}}{\mathrm{d}E}\frac{\Phi_\ell(E_\ell,X)}{\lambda_{\mathrm{int},l}(E_\ell)} + \sum_\ell \int_E^\infty \mathrm{d}E_\ell \frac{\mathrm{d}N^{\mathrm{dec}}_{\ell(E_\ell)\to h(E)}}{\mathrm{d}E}\frac{\Phi_\ell(E_\ell,X)}{\lambda_{\mathrm{dec},l}(E_\ell,X)}, \quad (3)$$

Source term

$$E_h^\gamma \frac{\mathrm{d}N_h}{\mathrm{d}E_h} = F_h$$

Impact of variation in prod. spectrum

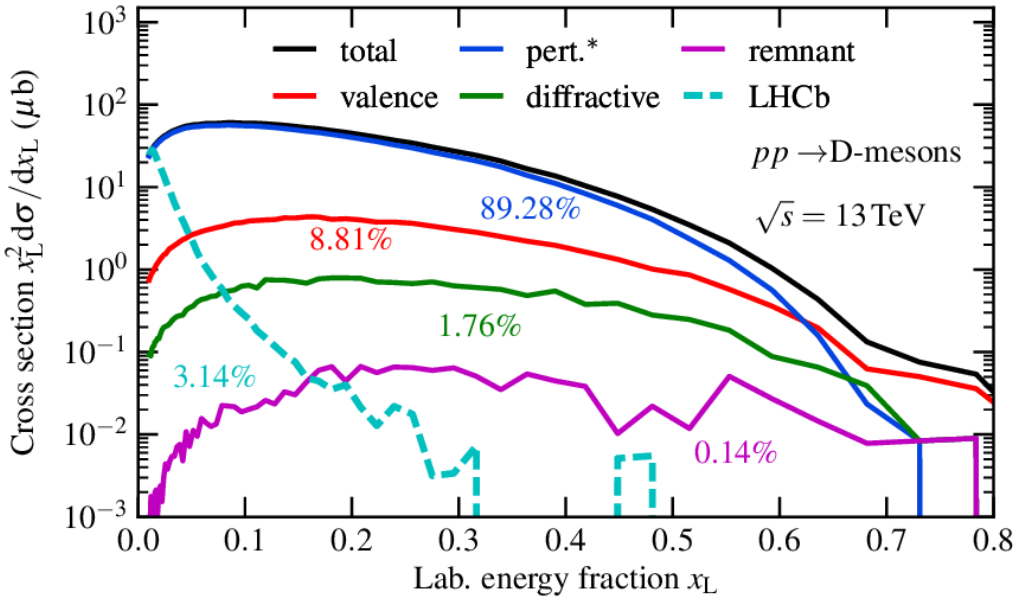


Phasespace coverage

LHCb only covers small fraction

Source term

$$E_h^\gamma \frac{\mathrm{d}N_h}{\mathrm{d}E_h} = F_h$$



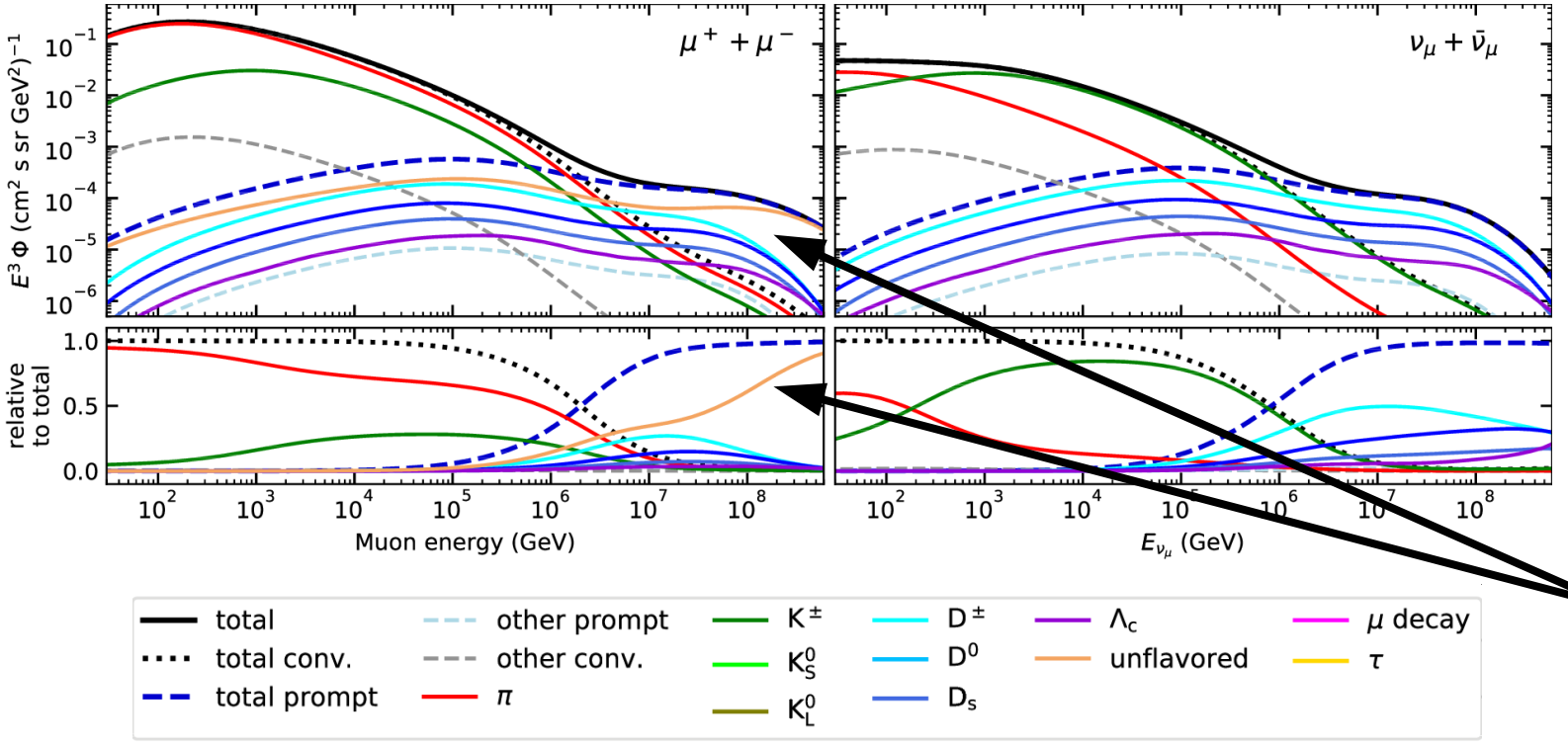
LHC detectors: not so great :(

Charm data

TABLE II: Experiments that collected data on charm production including the corresponding projectile-target configuration and the accessible longitudinal phase space. These data have been used for model development and parameter estimation.

Name	P_{Lab} (GeV)	$\sqrt{s}$ (GeV)	x_{F} spectrum	x_{F} coverage	Beam config.	Ref.
E-769	250	22	yes	$-0.1 < x_{\mathrm{F}} < 0.8$	p-Nuc	[48, 59]
EHS	400	27.4	yes	$0 < x_{\mathrm{F}} < 0.6$	p-p	[49, 60]
MPS	800	39	yes	$-0.1 < x_{\mathrm{F}} < 0.4$	p-p	[50]
HERA-B	920	42	no	$-0.1 < x_{\mathrm{F}} < 0.05$	p-Nuc	[51]
STAR	21 TeV	200	no	$-0.03 < x_{\mathrm{F}} < 0.03$	p-p	[53]
PHENIX	21 TeV	200	no	$-0.003 < x_{\mathrm{F}} < 0.003$	p-p	[54]
ALICE	4 PeV	2.76 TeV	no	$-0.005 < x_{\mathrm{F}} < 0.005$	p-p	[55]
	26 PeV	7 TeV	no	$-0.004 < x_{\mathrm{F}} < 0.004$	p-p	[56]
LHCb	26 PeV	7 TeV	no	$0.002 < x_{\mathrm{F}} < 0.1$	p-p	[57]
	90 PeV	13 TeV	no	$0.002 < x_{\mathrm{F}} < 0.1$	p-p	[58]

Calibrate charm with muon flux measurement ?



Prompt dominated by unflavored !

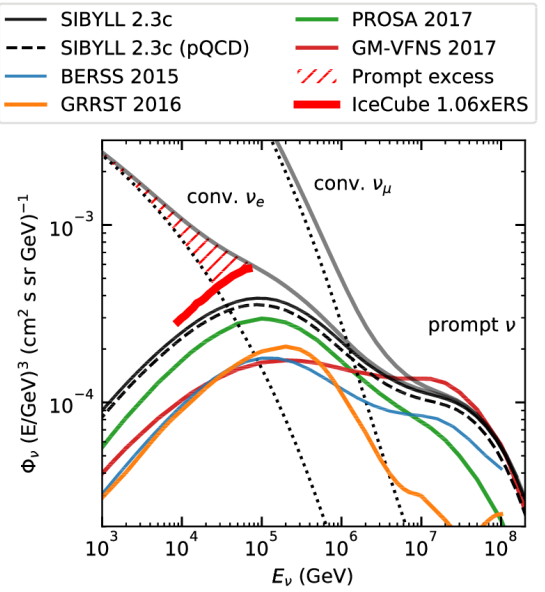
Summary

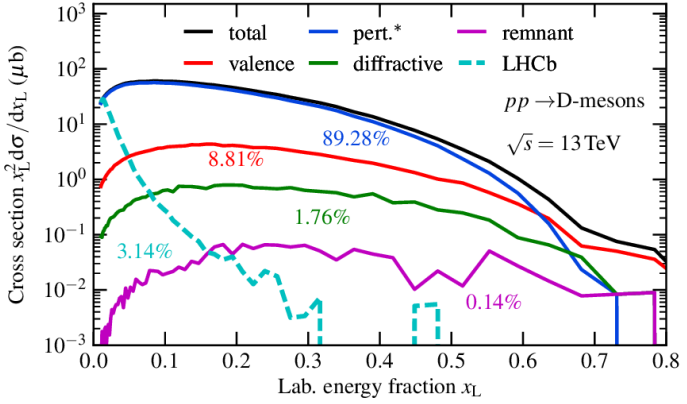
* high energy neutrino flux from prompt/charm
clear prediction by QCD

* prediction slightly depends on non-perturbative effects
(forward, low-x)

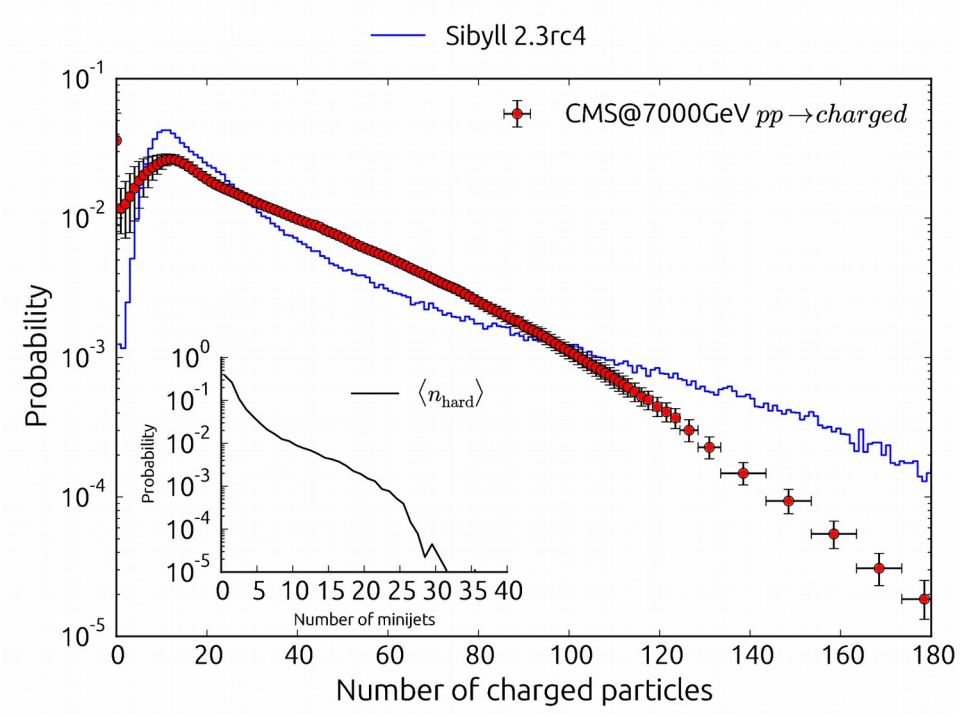
* model needs experimental input for forward region
(fingers crossed for pO at LHC, fixed target at LHC)

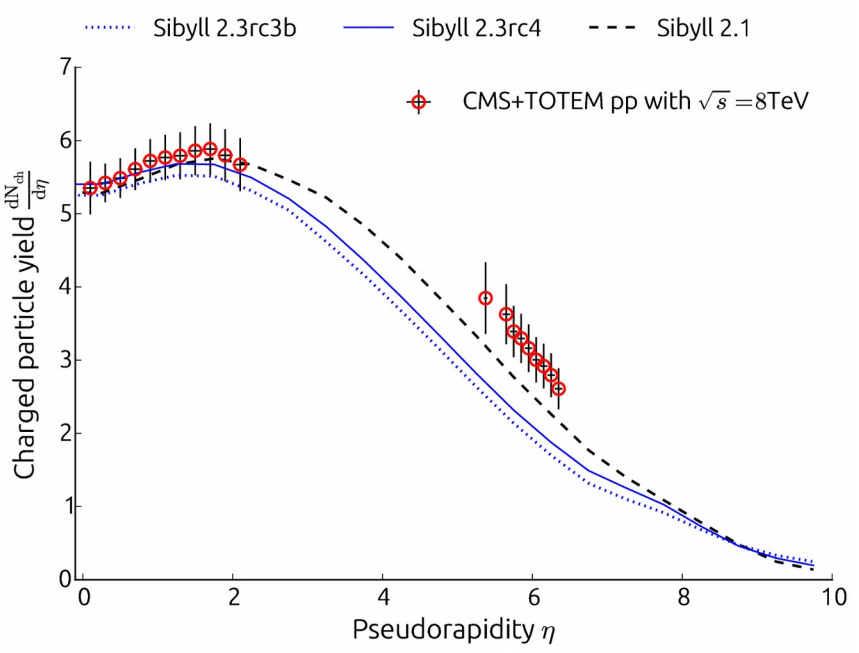
* future: charm in EPOS 3 (?)
→ nuclear effects, hard-soft correlation



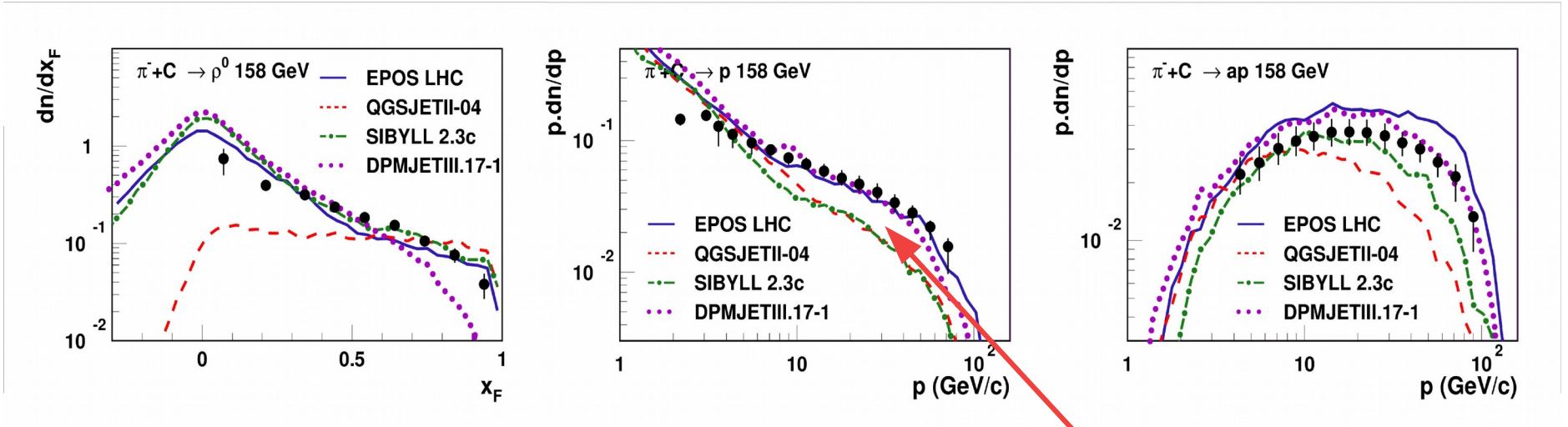


Opportunities for improvements



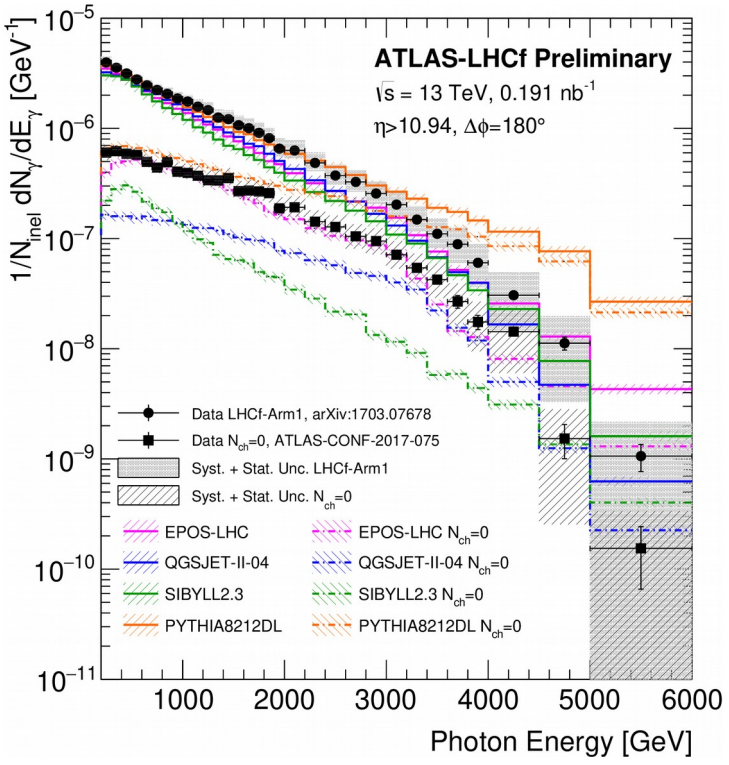


NA61

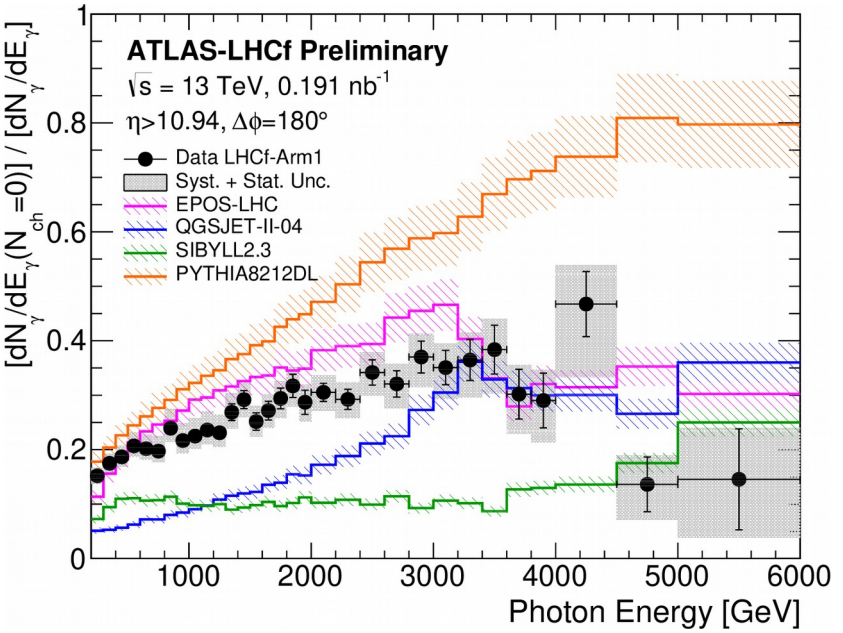

dn/dx_F
π⁻+C → ρ⁰ 158 GeV
EPOS LHC
QGSJETII-04
SIBYLL 2.3c
DPMJETIII.17-1
x_F
p.dn/dp
π⁻+C → p 158 GeV
p (GeV/c)
π⁻+C → ap 158 GeV

Enough ?

LHCf: Forward photons

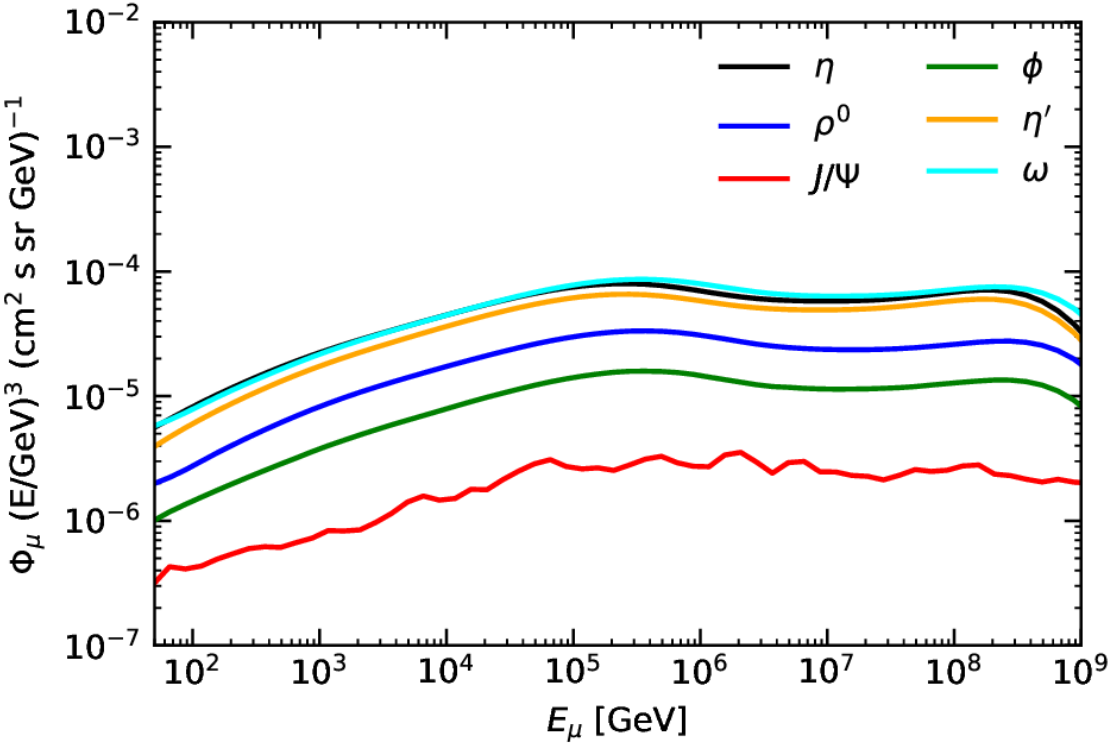


LHCf + ATLAS veto

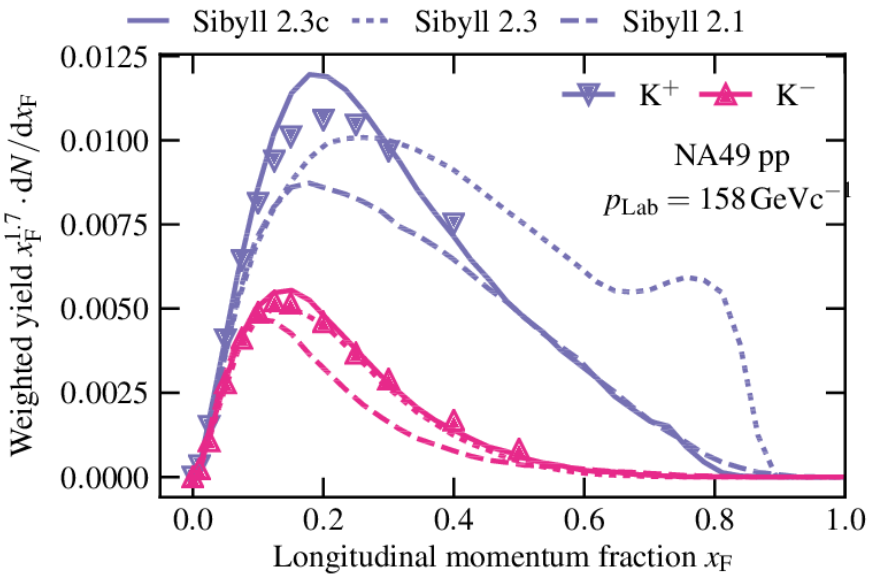


Diffraction?

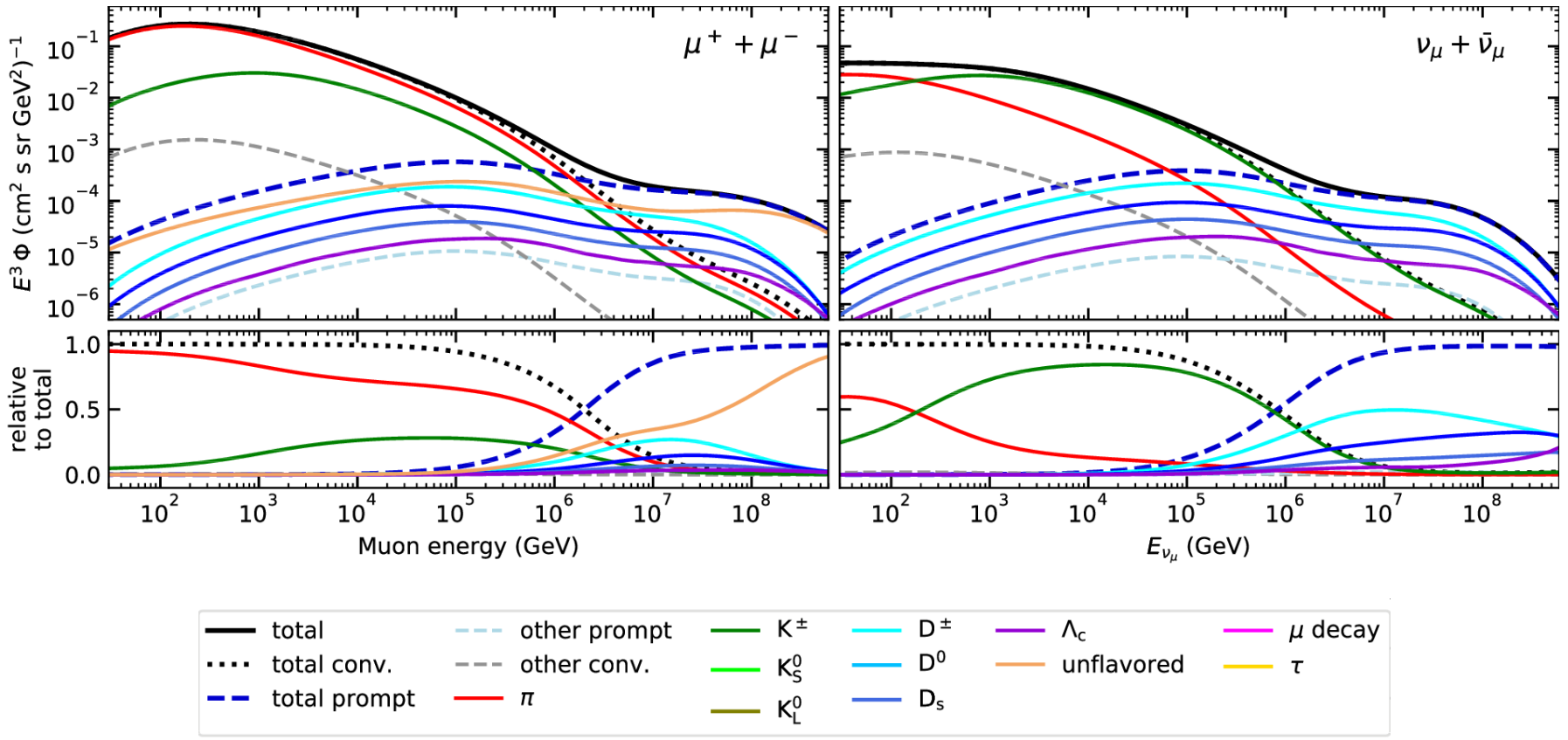
Unflavored prompt



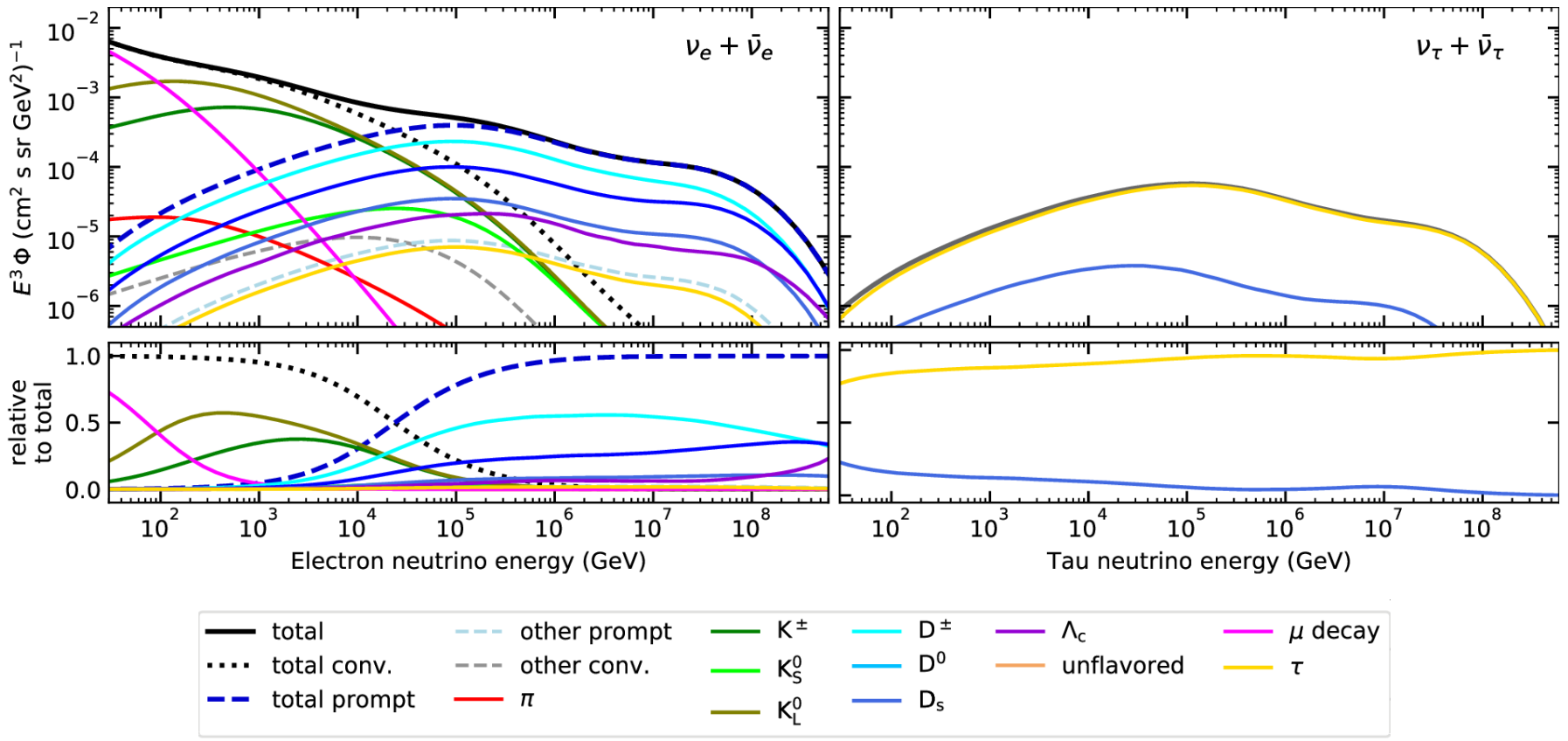
Phasespace coverage, low energy



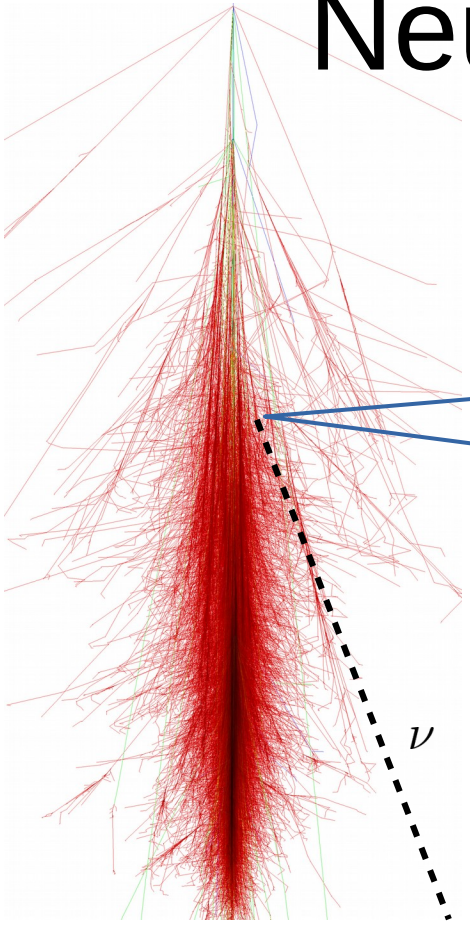
Atmospheric leptons



Atmospheric leptons



Neutrinos in the atmosphere

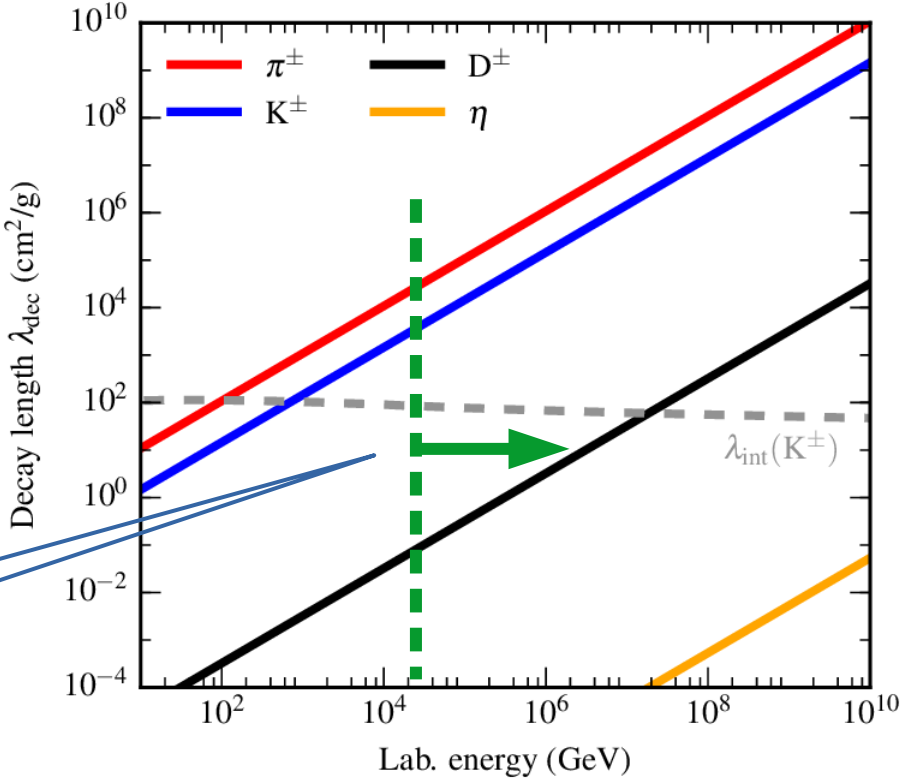


Decays of mesons

$$\pi/\mathrm{K} \rightarrow \mu + \nu$$

‘conventional’

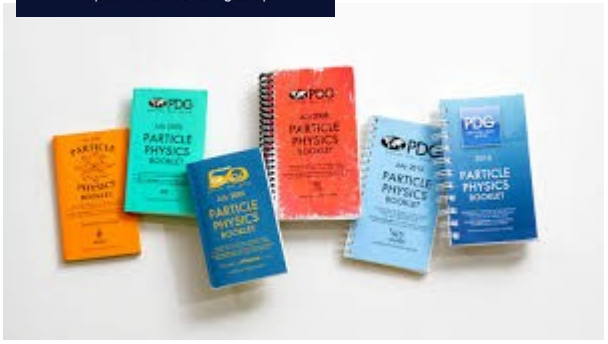
‘prompt’



(A. Fedynitch et al. 1806.04140)

Prompt neutrinos

Shortlived mesons with semi-leptonic decay



eg. charm

Which mesons exactly ?

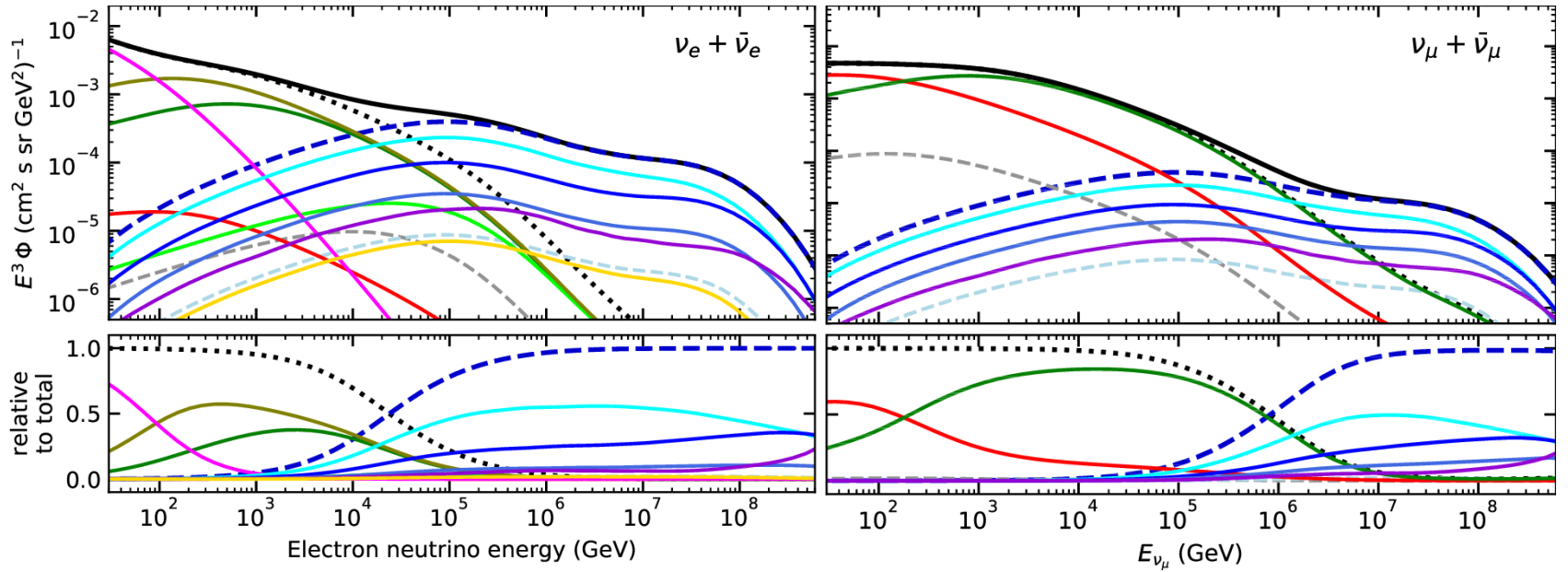
Citation: M. Tanabashi *et al.* (Particle Data Group), Phys. Rev. D **98**, 030001 (2018)

D^+ DECAY MODES

Most decay modes (other than the semileptonic modes) that involve a neutral K meson are now given as K^0_S modes, not as $\overline{K}^0$ modes. Nearly always it is a K^0_S that is measured, and interference between Cabibbo-allowed and doubly Cabibbo-suppressed modes can invalidate the assumption that $2\,\Gamma(K^0_S) = \Gamma(\overline{K}^0)$.

	Mode	Fraction (Γ_i/Γ)	Scale factor/ Confidence level
	Inclusive modes		
Γ_1	e^+ semileptonic	(16.07 ± 0.30) %	
Γ_2	μ^+ anything	(17.6 ± 3.2) %	
Γ_3	K^- anything	(25.7 ± 1.4) %	
Γ_4	$\overline{K}^0$ anything + K^0 anything	(61 ± 5) %	
Γ_5	K^+ anything	(5.9 ± 0.8) %	
Γ_6	$K^*(892)^-$ anything	(6 ± 5) %	
Γ_7	$\overline{K}^*(892)^0$ anything	(23 ± 5) %	
Γ_8	$K^*(892)^0$ anything	< 6.6 %	CL=90%
Γ_9	η anything	(6.3 ± 0.7) %	
Γ_{10}	η' anything	(1.04 ± 0.18) %	
Γ_{11}	ϕ anything	(1.03 ± 0.12) %	

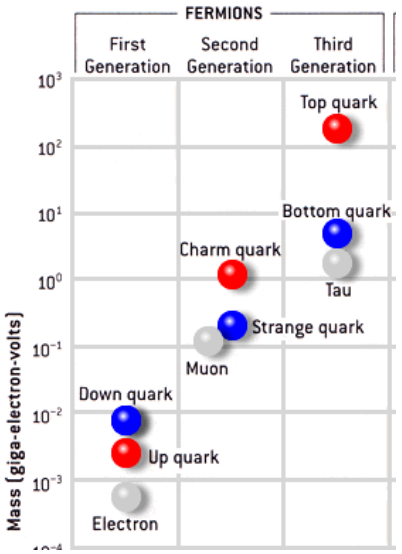
Atmospheric neutrinos

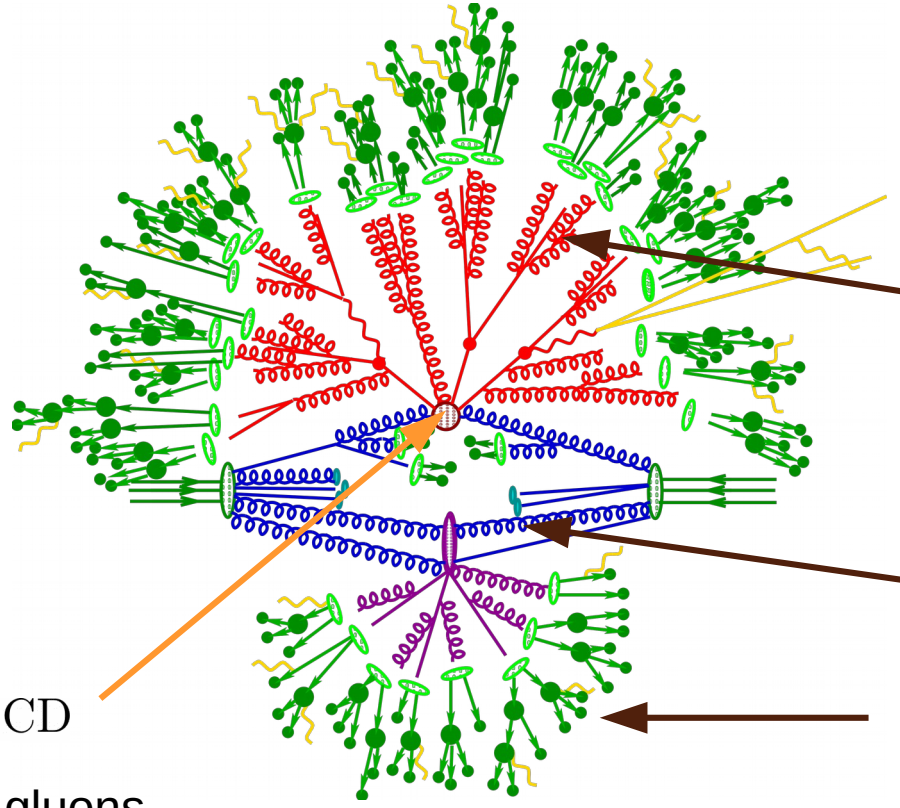


(MCEq, Fedynitch et al. 1503.00544)

→ For neutrinos: prompt ~ charm

Charm production in QCD





‘Parton shower’

‘soft’

Proton remnants

hadronisation

$m_c \approx 2\,\mathrm{GeV} \;\rightarrow\; \mathrm{pQCD}$

Quarks (charm) & gluons